A MODELLING STUDY FOR THE HEALTH RISK POSED BY NUCLEAR POWER PLANT IN BULGARIA AT DIFFERENT PARTS OF TURKEY

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ABSTRACT

A MODELLING STUDY FOR THE HEALTH RISK POSED BY NUCLEAR POWER PLANT IN BULGARIA AT DIFFERENT PARTS OF TURKEY

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In this study, following a severe accident at Kozloduy nuclear plant in Bulgaria how Turkey would be affected was investigated. The severe accident refers to core meltdown accident with catastrophic failure of containment. The model used is HySPLIT model developed in America. The worst day was predicted considering deposition of radionuclides. For initial runs, accidental release of I-131 and Cs-137 radionuclides was modeled for each day of year 2000 to find the worst day, seen to result from release beginning on April 7th 2000. After modeling release of all radionuclides for the worst day, radiation dose at different receptors, 12 most populated cities over Turkey has been calculated via different pathways. Late effects, fatal cancer, non-fatal cancer and hereditary risks, has been investigated for these receptors. The mostly affected part of Turkey was Marmara region and fatal cancer

risk therein was $7x10^{-2}$ %. The collective health risk throughout Turkey was approximately 20 600 people. The same approach was then applied for investigating health risk of proposed nuclear reactor at Akkuyu, Turkey. In this case, the worst day was resulted from release beginning on 21st of February 2000. The worst affected part was the narrow strip in Central Anatolia extending to the north-eastern cost and fatal cancer risk in this region was $3.4x10^{-1}$ %. The collective health risk over Turkey was approximately 30 600 people. The results showed that Kozloduy nuclear plant has dominating effect throughout Turkey, but proposed Akkuyu reactor affects very limited region.

Keywords: Nuclear, HySPLIT, accident, Kozloduy.

ÖZ

BULGARİSTAN'DAKİ NÜKLEER SANTRALDEKİ POTANSİYEL BİR KAZANIN TÜRKİYE'NİN DEĞİŞİK BÖLGELERİNDE OLUŞTURACAĞI SAĞLIK RİSKİNİN MODEL YARDIMIYLA İNCELENMESİ

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Bu çalışmada Bulgaristan'daki Kozloduy nükleer santralinin Türkiye üzerindeki sağlık riski araştırılmıştır. En kötü kaza senaryosu esas alınarak santraldan atmosfere salınan radyonüklitlerin atmosferdeki dağılımları Amerika'da geliştirilmiş olan HySPLIT modeli ile incelenmiştir. Kaza senaryosunun kor erimesine ilaveten koruma kabının katostrofik arızasını da içerdiği düşünülmektedir. Atmosferik modelleme ile en kötü günün seçilmesinde yerdeki birikim esas alınmıştır. İlk simülasyonlar 2000 yılının her günü, bu kaza senaryosundan atmosfere sadece Cs-137 ve I-131 radyonüklerinin salımı olduğu varsayılarak yapılmış ve en kötü birikimin 7 Nisan 2000 tarihinde başlayan 15 günlük simülasyon sonucu biriken salımdan kaynaklandığı görülmüştür. Tüm fisyon ürünleri en kötü gün için modellendikten sonra Türkiye genelinde en çok nüfusa sahip toplam 12 adet reseptördeki insanların, sindirim, solunum ve dış ışınlanma yolları ile maruz kaldığı radyasyon dozu ile ölümcül, ölümcül olmayan kanser ve kalıtımsal riskler hesaplanmıştır. En fazla etkilenen bölgenin Marmara Bölgesi ve Istanbul'da yaşayan insanların ölümcül kanser riskinin $7x10^{-2}$ %. olacağı görülmüştür. Tüm Türkiye genelindeki kollektif risk de yaklaşık 20 600 kişi olarak hesaplanmıştır. Aynı yaklaşımla Akkuyu'da kurulması düşünülen nükleer santral için de sağlık riski araştırılmıştır. Bu durumda en kötü birikimin 21 Şubat 2000 tarihinde başlayan 15 günlük simülasyon sonucu biriken salımdan kaynaklandığı görülmüştür. En fazla etkilenen bölgenin Kayseri, Niğde ve Nevşehir'i de içeren ve kuzey doğu kıyısına uzanan dar bir alan olduğu ve buradaki insanların $3.4x10^{-1}$ %'lik ölümcül kanser riski altında oldukları görülmüştür. Tüm Türkiye genelindeki kollektif sağlık riski de yaklaşık 30 500 kişi olarak hesaplanmıştır. Sonuçta Kozloduy santralinin tüm Türkiye genelinde daha fazla risk ortaya koyduğu, Akkuyu santralinin ise yalnızca dar bir alanı etkilediği görülmüştür.

Anahtar Kelimeler: Nükleer, HySPLIT, kaza, Kozloduy.

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LIST OF ABBREVIATIONS

BEIR: Biological Effects of Ionizing Radiation

Bq: Beckerel

BWR: Boiling water reactor

CANDU: Canadian deuterium uranium reactor

DOE: Department of Energy

EC: European Commission

ECMWF: European Center for Medium –Range Weather Forecasts

EPA: Environmental Protection Agency.

EU: European Union.

FNL: Final Run Achieve

GCR: Gas cooled reactor

GDAS: Global Data Assimilation System

HySPLIT: Hybrid Single Particle Lagrangian Integrated Transport

IAEA: International Atomic Energy Authority

ICRP: International Commission on Radiation Protection

LOCA: Loss of coolant accident

NCEP: National Centers for Environmental Prediction

NOAA: National Oceanic and Atmospheric Administration

NRC: Nuclear Regulatory Commission

OECD/NEA: Nuclear Energy Agency of Organization for Economic Co-operation and Development

PHWR: Pressurized heavy water reactor

PWR: Pressurized water reactor

RBMK: Graphite moderated boiling water reactor

Sv: Sievert

TEAŞ: Turkish State Electrical Utility

UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation

VVER: Water-cooled water moderated pressurized water reactor.

CHAPTER 1

INTRODUCTION

1.1. General

Though nuclear power is a good source of energy and is not generally a threat, a major reactor accident can lead to a catastrophe for people and environment. By definition, a major reactor accident would lead to the severe overheating and subsequent melting of the nuclear fuel, which would cause a substantial quantity of radioactive material escaping, after breaching several barriers, into the environment**.** The major health and environmental threat would be due to the escape of the fission products to the atmosphere.

There have been instances of nuclear reactor accidents like heavy water cooled and moderated reactor at Chalk River in Canada in 1952, graphite moderated gas cooled reactor at Sellafield in Britain in 1957, boiling water reactor at Idaho Falls in US in 1961, pressurized water reactor in Three Mile Island in US in 1979, graphite moderated water cooled reactor at Chernobyl in Ukraine in 1986, sodium cooled fast breeder reactor at Monju in Japan in 1995 (Makhijani, 1996). Among them, Chernobyl completely changed the human perception of radiation risk. On 26 April 1986 Ukraine suffered a major accident, which was followed by a prolonged release to the atmosphere of large quantities of radioactive materials. Radioactivity transported from Chernobyl was measured in North and South Europe, and in Canada, Japan and the United States as well. Only the Southern hemisphere remained free of contamination. This accident has shown that in the case of a severe nuclear reactor accident not only the country where the accident occurs but also the surrounding countries can be affected.

Unfortunately, Turkey is surrounded by the world's oldest design and threatening nuclear power plants, Kozloduy in Bulgaria, Metsamor in Armenia, Paks in Hungary, Dukovany in Czech Republic, Bohunice in Slovakia, Ignalina in Lithuania of which first three are the closest ones. Among them only the health risk associated with Kozloduy plant has been investigated in this study. These plants are depicted in Figure 1.1.

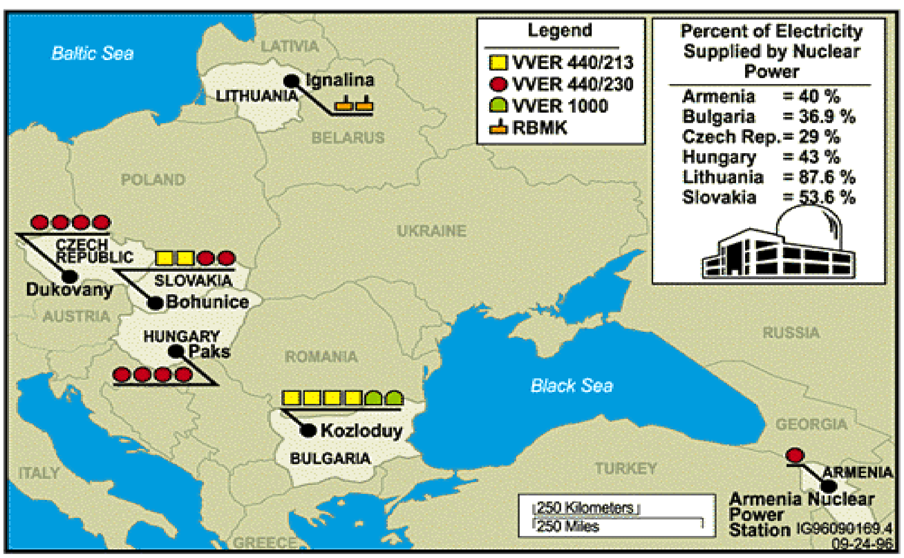


Figure.1.1. The Nuclear Power Plants around Turkey

Kozloduy Nuclear Power Plant is located in Bulgaria and it is only 300 km away from Turkish border. The old units of Kozloduy have been called the time bomb of the Europe and these were constructed to the designs and concepts worked out in the former Soviet Union during the 1960s. Therefore, the existing level of security corresponds to the safety concepts of that time. The comparison of the reactors' design with current safety standards reveals major safety deficiencies, particularly in the following two categories:

(i) There is essentially no protection for the public in the event of a major accident such as a large pipe break in the reactor coolant system, rupture of a reactor pressure vessel or large earthquake; and

(ii) The protection for the public against less severe design basis accidents such as a small pipe break is inadequate because of the lack of independence between existing safety systems and inadequate maintenance and operator training.

Official statistics shows that the most frequent causes of the accidents in the Kozloduy were equipment failure together with design errors (Nicolova, 1998). These will be discussed in detail in Chapter 2.

On the other hand, although Turkey doesn't use nuclear power for generating electricity, it has made five attempts to start a nuclear power program beginning in 1960. The Akkuyu site, licensed by Turkish Atomic Energy Authority in 1976, has several advantages. The first is its sea communications to bring in heavy machinery. The second is its proximity to centers of electricity consumption such as Adana, Konya, Antalya and Mersin. The area also has a record of relative seismic stability, although this has been disputed. Finally, the relative low density of population makes it safer in the unlikely event of an accident.

But Turkey postponed the decision to build the country's first nuclear power plant because of some financial and technical reasons. In this study, taking into account that cancellation of the nuclear power plant project doesn't mean that Turkey will avoid nuclear energy in the future, the health risk associated with that proposed nuclear power plant in Akkuyu also has been investigated.

1.2. Scope and Objectives of the Study

The main objective of this study is to investigate and compare the health risk associated with Kozloduy Nuclear Power Plant in Bulgaria and proposed Nuclear power plant at Akkuyu Turkey. Appropriate comparison of the two plants in terms of their risk on Turkey has been performed.

To achieve these goals, the study, was performed in two phases. In the first stage, atmospheric levels and deposition amount of different radionuclide, after a hypothetical major accident at Kozluduy and Akkuyu nuclear power plants, were determined with numerical modeling.

Actually the modeling study consisted of two phases in itself. In the first step, a study that ensures accuracy of model results was performed. This included among many sensitivity runs, the studies to determine suitable accident scenarios for this study, most suitable radionuclide to concentrate on, and most suitable years to select as the study period.

There are different types of nuclear accidents that can happen in a nuclear reactor. These different accidents result in emission of different quantities of isotopes to different altitudes in the atmosphere. An accident scenario that results in the highest emissions to the highest altitude was selected for this study. Since the approach was to select the worst-case scenario, the risks calculated for the population in different parts of Turkey are the highest possible risks.

Since the types of accidents that cause the highest emission depends on the design of the reactor, the possible scenarios were evaluated separately for the Kozluduy and Akkuyu power plants.

Two different radionuclides were selected for the modeling studies. These are I-131 that represents short-lived isotopes emitted as a result of accident and Cs-137 that represents long-lived isotopes emitted after the mishap in the reactor. The depositions of other isotopes were assumed to be similar with the concentrations and deposition of these two isotopes.

The study period was determined using meteorological data from two stations (İpsala and Çorlu) in Turkey. The surface wind speed and direction for several years from these stations were compared with the long term data (approximately 40 years) in the same stations. The year 2000 was selected, based on similarity with the long term records, as a typical year and was used as the study period in the study.

Once the input parameters were determined, the model was run for every day in the year 2000, for both nuclear reactors and two parameter were calculated; (1) cumulative deposition of isotopes to the grids in Turkey, in the 15 day period and (2) the ground level radioactivity that occurs in each grid and at every day. Since the emissions do not change from one day to another, the cumulative deposition and ground level concentrations are determined by the prevailing meteorological conditions at the time of accident. For each of the two reactors, the accident that resulted in the highest deposition and ground level activities were selected for the subsequent risk analysis.

The deposition and ground level activities of radioisotopes resulting from the two reactors were compared.

In the second step, lifetime dose commitment resulted from deposition and ground level activities were calculated for 70 years via three pathways, inhalation, ingestion and external exposure. Since it is not practical to perform the dose calculations at all grids on Turkey, radiation dose was calculated at the selected receptor points at different parts of Turkey. Finally the health risk in terms of stochastic effects at these receptors was investigated and the results were compared for the two reactors.

CHAPTER 2

BACKGROUND

2.1. Background Overview

This chapter includes of the review of the Kozloduy and Akkuyu nuclear power plants, the worst case accident and source term concepts which are the most important element for the accident analysis, the selection of the meteorological year, a brief description of the meteorological input fields, an overview of the HySPLIT, the transport model used for both accident simulations in this study. Radiation and risk terms are also introduced. These topics present fundamental information forming the basis of the subsequent health risk analysis study.

2.2. Kozloduy Nuclear Power Plant

Kozloduy nuclear power plant, the only nuclear plant in Bulgaria, is located 200 km to the north of Sofia and 5 km east of Kozloduy town at the Danube River bank. Kozloduy has operated six units of 3760 MW(t) power, four of which are VVER 440/V230 and the remaining two units are VVER 1000. VVER refers to water-cooled and water moderated pressurized water reactor of Soviet design. The number 440 refers to electrical power and 230 and 1000 are the name of the design. Units 1 and 2 were connected to the electricity grid in 1974 and 1975 and Units 3 and 4 in 1980 and 1982. The newest units 5 and 6 are of the VVER 1000-320 type and they started operation in 1988 and 1992 (EU, 1998).

Nuclear Energy Agency of Organization for Economic Co-operation and Development (OECD/NEA,1998) described general features of the VVER reactors: The standard VVER 440/V230 type reactors was developed in the Soviet Union between 1956 and 1970. The fuel in VVER 440 is slightly enriched (2.4% enrichment is used in a three year cycle) uranium dioxide. The pellets loaded in pressurized tubes are arranged in a triangular lattice structure called a fuel assembly. The core of the VVER 440 reactors is characterized by hexagonal geometry: the fuel assemblies have hexagonal form and the control assemblies are arranged on the basis of hexagonal symmetry. The core of a VVER 440 contains 349 standard fuel assemblies and 126 fuel elements per assembly. (see Appendix A for definition of nuclear terms). This type of reactors uses rack and pinion control rod drive mechanism. The part of the absorber part of the control assemblies is made of boron steel. The water in a VVER 440 is maintained at a high pressure approximately 12.5 Mpa. The heat from primary circuit is removed in six coolant loops using horizontal steam generators, which is probably the most specific feature of all VVER's. The secondary side of the steam generators contains large water volumes covering the heat transfer tubes. The accident localization system was designed to handle only one 100 mm pipe rupture. The VVER/V230 has no containment and emergency core cooling systems and auxiliary feed water system similar to those required in Western plants. The plant instrumentation and control, safety system, fire protection system, quality of materials, construction, operating procedures, safety culture are below Western standards. (OECD/NEA, 1998)

The VVER 1000 is a newer version of VVR 440/V230. It has common safety features with reactors in the Western countries, was designed between 1975 and 1985. The core of a VVER 1000 contains 163 standard fuel assemblies and 312 fuel elements per assembly. The fuel assemblies are in the form of triangular lattice. The fuel is slightly enriched (4.4 % enrichment is used in a three year cycle). The hexagonal structure of the core structure is the same as VVER 440s. The water in a VVER 1000 is maintained at a high pressure approximately 15.7 Mpa. The standard VVER 1000 unit comprises larger steam generators than those of the VVER 440 and has only four primary coolant loops. The unit has a full pressure large containment structure. The containment is designed to cope with a double-ended rupture of any single primary system pipeline with a diameter of 850 mm. In VVER 1000 reactor types the control rods are similar to PWR clusters. Absorber material is B_4C in VVER 1000s and control rod drive mechanism is electromagnetic type. Core cladding material is Zr1%Nb alloy which has good operational experience at low temperature and more resistant to oxidation than zircaloy used in PWRs (OECD/NEA, 1998). (See Chapter 2.3 for details).

Enconet Consunting (1997) stated that the old units 1-4 of Kozloduy were constructed to the designs and concepts worked out in the former Soviet Union during the 1960s. The main problems include the lack of containment, poor accident localization system, low seismic safety standards and embitterment of the metal construction. The closure of the problematic four units of the plant has been demanded by the world' respective agencies, while Bulgaria is seeking to operate them as long as possible by implementing some modernization measures due to it's dependence on nuclear power. Experts claim that most of these measures implemented since 1992 have not been substantial from a safety perspective. For example the systems for the localization of the maximum risk at the coolant system were upgraded for tubes with a diameter up to 100 mm, while the biggest pipes at the older units have a diameter of 500 mm (EU, 1998).

The first agreement between the European Bank for Reconstruction and Development and the Bulgarian Government envisaged that units 1 and 2 be closed in 1997 and units 3 and 4 in 1998 (Nikolova, 1998). Though the funding of the Nuclear Safety Account was fully disbursed and invested in different measures for temporary safety upgrades, the closure of the units didn't happen due to resistance from Bulgarian officials, lack of investments in rehabilitation of other power stations or construction of new ones as well as ignorance of energy efficiency measures.

The will of the Bulgarian government to start accession negotiations with the EU led to the Memorandum of Understanding signed in November 1999. This required closure of units 1 and 2, but specified that agreement on the closure of units 3 and 4 must be reached in 2002. The EC maintains its position that units 3 and 4 must close in 2006, while the Bulgarian government argues for closure dates of 2008 and 2010 for units 3 and 4 respectively. At the end, on 31 December 2002 the first two old units of the Bulgarian Kozloduy were shut down after 10 years of demands for their closure and the Government agreed to close units 3 and 4 in 2006 but asked the EU for a peer review in 2003 to say whether the upgrades made during last years brings the safety up to an acceptable level (EC,2002).

2.3. Worst Case Accident Scenario

There are large number possibilities for a potential accident in a nuclear reactor, starting from simple pipe rupture, which does not cause any emission of radioisotopes and all the way to lost of the integrity of containment, which is catastrophic in terms of isotope emissions to the atmosphere (Baferstam, 1995). Since highest possible impact of the Kozloduy and Akkuyu nuclear power stations are investigated the accident scenario should also be the one which causes the highest emission of radioisotopes to atmosphere.

International Atomic Energy Agency (IAEA) Tecdoc-955 identifies four different core damage states for the light water reactors: (see Appendix A for different reactor types)

(i) Leakage of normal coolant following a steam generator tube rupture accident that does not involve core damage,

(ii) Leakage of spiked coolant following a steam generator tube rupture accident that does not involve core damage. Spiked coolant assumes all the non-nobles in the normal coolant increase by a factor 100 to estimate the maximum spiking sometimes seen with rapid shutdown or depressurization of the primary system,

(iii) A gap release assumes that the core is damaged all fuel pins have failed, releasing the gaseous fission products contained in the fuel pin gap,

(iv) A core melt release assumes that the entire core has melted, releasing a mixture of isotopes believed to be representative for most core melt accidents.

2.3.1. Accident Progression:

Among different core damage states mentioned in previous part, the progression of the *core meltdown accident* will be discussed, because the radiological consequences of this accident is generally assumed to be the worst, as it causes the highest amount of fission product release from the core.

Boeck (1997), who studied how containment performance affects the severe accident at nuclear reactors, described in-vessel phenomena. In a nuclear power station large amount of radioactive substances are present in the fuel in the reactor core after a period of operation. During normal operation these are largely bound with the fuel material and contained inside the fuel cladding, which surround the fuel material. As a result of the heat produced by the radioactive decay of the active elements, known as the “decay power”, the fuel temperature will begin to rise in the case of insufficient cooling of the core. The LOCA which is defined as accident that result from a loss of coolant inventory at rates that exceed the capability of the reactor coolant makeup system is assumed as initiating event in this study. Safety engineered cooling systems, which are very limited in VVER 440’s, are required if the normal cooling systems fail. If such a supplementary coolant system does exists, accidents will proceed without any overheating of the fuel, thus without any extensive fuel damage and release of radioactivity. In the case of more severe accident scenarios, which formed bases for this study, the core loses its cooling and will be damaged by overheating and melt, radioactive substances will be released to the environment.   In Kozloduy nuclear power station the two VVER 440 reactors do not have supplementary coolant system and overheating in the case of an accident is likely to result in core melt down described above.

In a light water reactor (like Kozloduy) failure of the cladding is expected when the fuel cladding temperature exceeds 900˚C. When this happens, gaseous fission products contained in the gap are swept to the coolant channels and the cladding will begin to chemically react with steam giving off hydrogen and heat. At temperatures above 1300˚C the reaction between steam and cladding becomes powerful thus accelerating the heating up the fuel. Radionuclides released during heat up from the core enter first the gap between the fuel pellets and the cladding. The heating up of the fuel as a result of decay heat and the chemical reaction between cladding and steam means that within about one hour of the fuel being uncovered, the temperature at the center of the core will reach such high values that the fuel will begin to melt. Finally the hot molten core material will collect at the bottom of the reactor pressure vessel, melt through the bottom, and gradually drop in the reactor cavity, which is part of the containment compartment (OECD/NEA, 1998). This sequence of steps is only possible if the redundant emergency core cooling system fail after the event initiating the accident.

2.3.2. Containment Function:

Boeck (1997) stated that normally four barriers (ceramic structure of the fuel, the fuel rod cladding, the reactor coolant system pressure boundary, containment pressure boundary) protect the public from the release of radioactive material generated in nuclear fuel. In most core melt accidents three barriers would be progressively breached, and the containment boundary represents the final barrier to release of radioactivity to the environment. The containment can fail early, late, be bypassed during the accident leading to the radiological consequences that are completely different. He described these types of failure in such a way that: Early containment failure is the failure prior to or shortly after the core debris penetrates the reactor vessel. An early failure as in the case of Chernobyl power plant is important because it tends to result in shorter warning times for initiating off-site protective features and it also reduces the time for deposition of the radioactive materials within the containment. The late containment failure is the failure of the containment after the molten core has penetrated the reactor vessel. In some accidents containment building may completely be bypassed, which allows primary coolant and fission products accompanying it to escape to environment without having been discharged into the containment atmosphere. Slaper (1994) who studied the risk of European nuclear power reactors, also identified another category in which the containment may remain intact even the core is severely damaged in some cases, like Three Mile Island accident in the US in 1979. In such a case radioactive release to the environment is minimized.

2.3.3. Source Term:

Source term is the key element of any accidental consequence assessment. The Report of US Nuclear Regulatory Commission, Nureg 1150, (1990) assessed the risk of five different nuclear power reactors in US and defined the source term as characterized by the fractions of the core inventory (which refers to amount of isotopes that exists in the core during normal operation of the plant) that are released to the environment, as well as duration of the release and the elevation of the release. Slaper (1994) stated that total amount of release depends on accident scenario, reactor type and also core inventory determined by thermal power of the reactor and also varies with the fuel burn up and cumulative yield of the fission products, which have been broadly discussed in Appendix A. Appendix B provides lists of reactor inventories for the main dose contributing nuclides, based on a reactor with 3000 MW(t) thermal power in the middle of the fuel cycle. This inventory was taken from Slaper' s study. A reactor with 3000 MW(t) thermal power is considered representative for a reactor with an electrical power of 1000 MW(t). For reactors with different electrical powers, the reactor inventories are scaled directly proportional to its electrical power and can be calculated from the inventory based on the 1000 MW(t) electrical power. The inventory of VVER 440 reactor was calculated in this way.

Radioactive species in the reactor inventory are generally separated into different groups based on their chemical or physiological behavior. US NRC Nureg 1150, (1990) groups' radionuclides according to their potential for causing early fatalities, latent cancer fatalities. Nine groups are used to represent 60 radionuclides that are considered to be most important in terms of their effects in the environment. These groups include, noble gases consisting of xenon and krypton, iodine group, which consists of iodine isotopes, alkali metals group that includes Cs and Rb isotopes, Ba group including Ba isotopes, Sr group that consists of Sr isotopes, tellurium metals group consisting of Te, Se and Sb species, cerium group consisting of Ce, Pu and Np isotopes, ruthenium group consisting of Co, Ru, Rh, Pd, Mo and Tc species and lanthanium group that includes La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Am, Cm, Ny isotopes.

2.4. Atmospheric Dispersion and Radionuclide Release

2.4.1. Theoretical and Physical Basis of Dispersion:

Atmosphere is the most important way to transport the radionuclides released from a nuclear accident over distances. IAEA -Tecdoc 379 (1986) explains atmospheric dispersion phenomenon, atmospheric dispersion model and features of the atmosphere affecting the dispersion in such a way that: Atmospheric dispersion implies the transport of the effluent by winds and the concurrent diffusion by atmospheric turbulence. An atmospheric dispersion model is a mathematical relation between the quantity (or rate) of effluent release and the distribution of its concentration in the atmosphere. The processes contributing the dispersion may be classified into:

(i) Transport and trajectory process (advection)
(ii) Diffusion by turbulent eddies
(iii) Modifying process e.g. depletion

(i) Transport and trajectory process

Most models consider the source to be an ideal point source unaccompanied by energy release and not interfering with ambient conditions. However real sources are of finite size and have momentum and buoyancy. There is the initial kinetic energy due to initial discharge energy and the thermal energy when the effluents are above ambient temperature. This causes the plume to rise above its release point while simultaneously dispersing. These effects are important in regions near to the source. For longer distances, the ideal point source assumption is more appropriate for radionuclide releases.

Puff is a term, which is used in models that follows the movement of air masses. A puff of an inert gas (which will be called a pollutant) released to the atmosphere travels with the wind and develops into a progressively expanding cloud due to turbulent eddies. The current centers of a series of contiguous puffs define a plume trajectory. It's trajectory is determined by the wind field and its variation with time. A continuous release may be considered as a consecutive series of puffs. As the inert pollutant is transported it will circumnavigate the globe depending on wind field and the latitude. In the middle latitude, this is about 3 weeks. A non-inert pollutant will be continuously subject to depletion process during its dispersion and may never become spread through long distances (IAEA -Tecdoc 379, 1986).

(ii) Diffusion by turbulent eddies

Wind speed and wind direction change continuously with time in three dimensions. A long-term wind direction record shows a conglomeration of rapid fluctuations. This continuous fluctuation is called turbulence and is a basic characteristic of the atmospheric motion responsible for eddy diffusion. The part of the eddy size spectrum taking part in the diffusion process depends upon the size of the cloud of dispersing material. Eddies much smaller than the cloud or plume size cause a minor redistribution of the effluent within the plume, while eddies much larger than the plume or cloud cause it to be bodily shifted without altering the concentration distribution inside the plume. As the cloud travels downwind, the scale of eddy motion responsible for atmospheric diffusion increases continuously (IAEA -Tecdoc 379, 1986).

(iii) Modifying Process (Atmospheric Removal):

Process removing radionuclides from the atmosphere, and interaction of nuclides with the Earth's surface are very important for modeling atmospheric transport and consequences of nuclear accidental releases. Especially for long-term consequences, the radioactivity deposited contributes more to the total dose to humans than the direct exposure from the plume (Baklanov and Serensen, 2000). Three basic removal mechanisms contribute to further depletion of activity are dry deposition, wet deposition and radioactive decay.

Dry deposition plays an important role for most of the radionuclides except noble gases. It is different for noble gases, aerosols, elemental and organically bound iodine, so different materials have different dry deposition velocities on different surfaces. Dry deposition is also dependent on weather conditions in terms of wind speed and atmospheric stability. Gravitational settling strongly effects dry deposition especially for heavy particles (radios >1 μm) (Baklanov and Serensen, 2000).

Material can also be removed from a plume by the action of rain. Two separate process, termed washout and rainout, may be considered. Washout is the removal of material by raindrops falling through a plume (below-cloud removal) while rainout is removal of material incorporated into raindrops within the cloud (in-cloud removal). Both rain and snow can remove pollutants from the atmosphere. It is shown that the washout coefficient strongly depends on the particle size. This dependence, however, is not included in most atmospheric dispersion models (Baklanov and Serensen, 2000).

The effect of radioactive decay is treated simultaneously for the whole group of nuclides in the formulation of radioactive chains when the daughter nuclides are borne and will grow in the plume with a decay of the parent nuclides (Pecha et al., 2001). Short-lived radionuclides airborne concentrations decline rapidly with distance from the source. For this reason these radionuclides with half-lives of a few hours or less are not radiologically important at large distances. With typical wind speed of about 10 ms^{-1}, the noble gas ^{135}Xe, which has a half-life of 9.2 hr, decays to about one eight of its original activity in the time taken to travel 1000 km. On the other hand, some radionuclides commonly found in airborne effluents of nuclear facilities have extremely long radioactive half-lives and in addition, because they are gases, are not efficiently removed from the plume by other processes, such as wet and dry deposition. The most well-known and important radionuclide is ^{85}Kr ($t_{1/2}$ =10.7 year) (IAEA Tecdoc-379, 1986).

Atmospheric resuspension may be a secondary source of contamination after a release has stopped. This source of exposure was important for the Chernobyl liquidators and for other people located near the accident site (Fogh et al., 1998).

2.4.2. Features of the Long Range Transport:

As material disperses over longer distances its travel is affected by larger areas of the atmosphere and features not considered in short range modeling have to be taken into account. (for further details about atmospheric dispersion models see Chapter 2.4.3.) According to the IAEA Tecdoc-379 these include:

(i) Vertical variation of atmospheric conditions encountered as plumes grow, including wind direction shear and the presence of elevated inversions.

(ii) The changes in atmospheric conditions, such as wind velocity, stability and mixing layer depth during the travel of the plume.

(iii) The spatial variation of atmospheric conditions which means that data obtained at a single meteorological situation near the release point may not be representative of conditions over the region through which the plume is dispersing.

The net effect of wind shear is to increase the effective horizontal dispersion. The magnitude of wind direction shear varies during day and night. The wind shear may be very strong at night due to small vertical eddy sizes, which leads to a decoupling of layers separated by only moderate heights.

Also presence of elevated inversions affects the long-range transport and dispersion process. The base of the stable layer in the atmosphere may vary from a few tens of meters to a few kilometers. While the ground inversion dissipates after sunrise, these upper inversions can persist though the height of the base may change. The stable layer is like a lid offering a barrier to the vertical growth of the diffusing cloud. If conditions persist for long enough the dispersing material will spread throughout the mixing layer. Increases in the depth of mixing layer allow the material to disperse through the deeper layer of the atmosphere. Decreases in the depth cause some material to be trapped in the stable layers above the boundary layer and be prevented from diffusing to ground level.

2.4.3. Atmospheric Dispersion Models:

The definition of the term "atmospheric dispersion model" was made in Chapter 2.4.1. IAEA-Tecdoc 733 (1994) describes the uses of real time models as a decision aid in the case of large radionuclide releases to the atmosphere. According to this report numerous atmospheric dispersion models have been developed over the years. The available models range from simple Gaussian, based on analytical solution of the transport and diffusion equations, to three-dimensional numerical models that require forecasting the meteorological variables on scales ranging from a few tens of kilometers to hemispheric.. This spectrum of model capability can be divided into the following three generic categories: (IAEA Tecdoc-733)

Type1: Gaussian models. These models can provide dispersion process for distances out to 5-10 km from the source point. They cannot, however, simulate dispersional process over complex terrain and/or some real meteorological conditions such as calms, wind shear and non-homogenous winds.

Type 2: Two-dimensional puff or trajectory models. These models can accept multiple wind speed and direction measurements from more than one point and provide a more realistic estimate of the plume trajectory and concentration patterns for distances beyond 5-10 km.

Type 3: Three-dimensional models. These numerical models use multiple wind measurements in both the horizontal and vertical directions, include terrain effects and vertical and horizontal wind shear, and treat more realistically parameter variables such as surface roughness, deposition and variable atmospheric stability. Numerical modeling is widely used to study long-range airborne transport and deposition of radioactive matter after a hypothetical accident (Rigina and Baklanov, 2001)

Since the long range transport of radionuclides is mentioned in this study, one of the three dimensional numerical models, the HySPLIT model has been selected.

2.5. Description of HySPLIT Model:

HySPLIT, Hybrid Single Particle Lagrangian Integrated Transport model was developed in NOAA Air Resources Laboratory in the United States for calculating the trajectories of air parcels, or the transport, dispersion, and deposition of pollutants (Draxler and Hess, 1997). User supplied inputs for HySPLIT calculations are pollutant species characteristics, emission parameters, gridded meteorological fields and output deposition grid definitions. The horizontal deformation of the wind field, the wind shear, and the vertical diffusivity profile are used to compute dispersion rate. Gridded meteorological data are required for regular time intervals. The meteorological data fields may be provided on one of the different vertical coordinate system: Pressure-sigma, pressure-absolute, terrain-sigma or a hybrid absolute-pressure-sigma. The model can be configured to treat the pollutant as particles, or Gaussian puffs, or as top/hat puffs. The term Hybrid refers to the additional capability of HySPLIT to treat the pollutant as Gaussian or top/hat puff in the horizontal while treating the pollutant as a particle for the purposes of calculating vertical dispersion. An advantage of the hybrid approach that is the higher dispersion accuracy of the vertical partical treatment is combined with the spatial resolution benefits of horizontal puff splitting. All model runs for this work were made in the default hybrid particle/top-hat mode.

2.5.1 Meteorological Input Fields

The meteorological input data for all simulations including sensitivity runs were provided from FNL archive. The 6-hourly archive data come from National Weather Service’s National Centers for Environmental Prediction (NCEP)'s Global Data Assimilation System (GDAS) in the Unites States. The National Weather Service's National Centers for Environmental Prediction (NCEP) runs a series of computer analyses and forecasts operationally. One of the operational systems is the GDAS. The GDAS is the final run in the series of NCEP operational model runs; it therefore is known as the Final Run at NCEP and includes late arriving conventional and satellite data (Petersen and Stackpole, 1989). It is run 4 times a day, ie, at 00, 06, 12, and 18 UTC. Meteorological fields for FNL archive data contain either the first 15 days of the month or the rest of the month.

The upper level FNL data are output on the following 13 mandatory pressure surfaces: 1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100, 50, and 20 hPa. The upper air data field include temperature in [ºK], u and w component with respect to grid in [m/s], perssure vertical velocity in [hPa/s], geopotential height [gpm] and vertical humidity [%]. The surface data fields provided are 2 m temperature in [ºK], 10 m u and w components in [m/s], surface pressure in [hPa], surface temperature in [ºK], total precipitation (6 hr accumulation) in [m], momentum flux u-component at surface in [N/m^2], momentum flux v-component at surface in [N/m^2], sensible heat net flux at surface in [W/m^2], latent heat net flux at surface in [W/m^2], downward short wave radiation flux at surface in [W/m^2], relative humidity at 2 m AGL in [%], volumetric soil moisture content fraction of layer 0-10 cm below ground in [fraction], total cloud cover for entire atmosphere in [%]. The meteorological data for HySPLIT model is always re-mapped internally to a common terrain following vertical coordinate system.

2.5.2 Model Applicability to Emergency Response:

Cs-137 release from Chernobyl accident was re-run by HySPLIT to illustrate its applicability to nuclear emergency response situation. The meteorological data set was obtained from European Centre for Medium-Range Weather Forecasts (ECMWF) 1995. HySPLIT was run assuming the release rate of 10^{15} Bq hr^{-1} of Cs-137 for the first 24 hour distributed uniformly in the layer 750-1500 m. In general, considering the model is using only forecast precipitation fields, the model performance is good. (Draxler and Hess, 1998) Although the radioactive release occurred for a 10-day period, the limited 5-day forecast data file permitted a realistic simulation of the first day's release.

2.6. The Proposed Nuclear Power Plant At Akkuyu

The proposed nuclear power plant in Akkuyu is assumed as 1000 MW(t) pressurized water reactor offered by Mitsubishi-Japan in this study. The Akkuyu site is on the Mediterranean coast.

The PWR, the assumed type of the Akkuyu plant, was one of the first types of power reactors developed commercially in the United States (Lamarsh, 1983). This type was initially developed not to generate electricity, but to provide steam for a turbine to provide motive power for a submarine. The first step in the chain was the Zero Power Reactor-1, a critical facility for design studies in 1950.

The report of OECD/NEA (1998) also describes the features of the PWRs so as to compare those of the VVERs. Some specific features are as followed: The core of the PWR reactors is characterized by square geometry. The fuel in PWR reactors is slightly enriched (from 2 to 4 %) uranium dioxide. The pellets loaded in zircolay tubes are arranged in a square lattice. The number of fuel assemblies is 121 and number of fuel element per assembly is 179 in two-loop reactors. PWRs are constructed of different core materials from those of VVERs. Probably the most significant difference is the core cladding material, which is zircolay in PWRs. The water in a PWR is maintained at a high pressure, approximately 15.5 MPa. Large PWR systems utilize as many as four vertical steam generators.

Control of PWR is accomplished by the use of control rods and by chemical shim system, which involves a neutron absorber (usually boric acid) dissolved in the coolant water. The control rods are made of neutron absorbing material like cadmium.

In December 1996 The Turkish State Electrical Utility TEAŞ invited bids from foreign reactor vendors. The three bidding consortia were Westinghouse /Mitsubishi (UK/USA/Japan), Atomic Energy Canada Limited (Canada) and Nuclear Power International (a partnership of Siemens of Germany and Framatome of France). The new station would be one of three reactor types; pressurized water reactors, boiling water reactors, pressurized heavy water reactors. The selection of winning of nuclear vendor to build the Akkuyu Plant was first supposed to have been made in June 1998. The selection was delayed more times and in July 2000 Turkey postponed a decision on bids to build the countries first nuclear power plant. There has been some reasons for this postponement like the financial burden of external credits was unbearable by Turkish economic situation, it would be better to build natural gas plants with low capital cost an short construction period, it would be better to continue current hydro and natural gas projects and wait for new generation nuclear reactor technology with decreased capital cost and there may rise an opportunity to use solar or wind energy (Aktürk, 2001)

2.7. Radiation and Health Risk

2.7.1. Radiation and Dose Terms:

The report of International Commission on Radiation Protection (ICRP-60, 1990) defines the ionization as the process by which atoms lose, or sometimes gain electrons and thus become electrically charged, being known as ions. Ionizing radiation is the term used to describe the transfer of energy through space in the form of either electromagnetic waves or subatomic particles that re-capable of causing ionization in matter. When ionizing radiation passes through the matter, energy is imparted to the matter as ions are formed.

IAEA (2000) described the term activity, dose and different dose quantities in its Safety Glossary in such a way that: The quantity for an amount for radionuclide in a given energy state at a given time defined as activity. The SI unit of activity is the reciprocal second (s^{-1}), termed the Beckerel (Bq). A measure of energy deposited by radiation is called dose. Absorbed dose is defined as the mean energy imparted by ionizing radiation to matter per mass of matter. The unit of absorbed dose is J/kg, termed the Gray (Gy). Dose equivalent is the product of the absorbed dose at a point in the tissue or organ and the appropriate quality factor for the type of radiation giving rise to the dose. Effective dose is defined as the sum of the weighted equivalent doses in all the tissues and organs of the body. Committed dose is defined as the lifetime dose expected to result from an intake. The unit of the dose equivalent, effective dose and committed dose are J/kg, termed the Sievert (Sv).

2.7.2. Exposure of the Population:

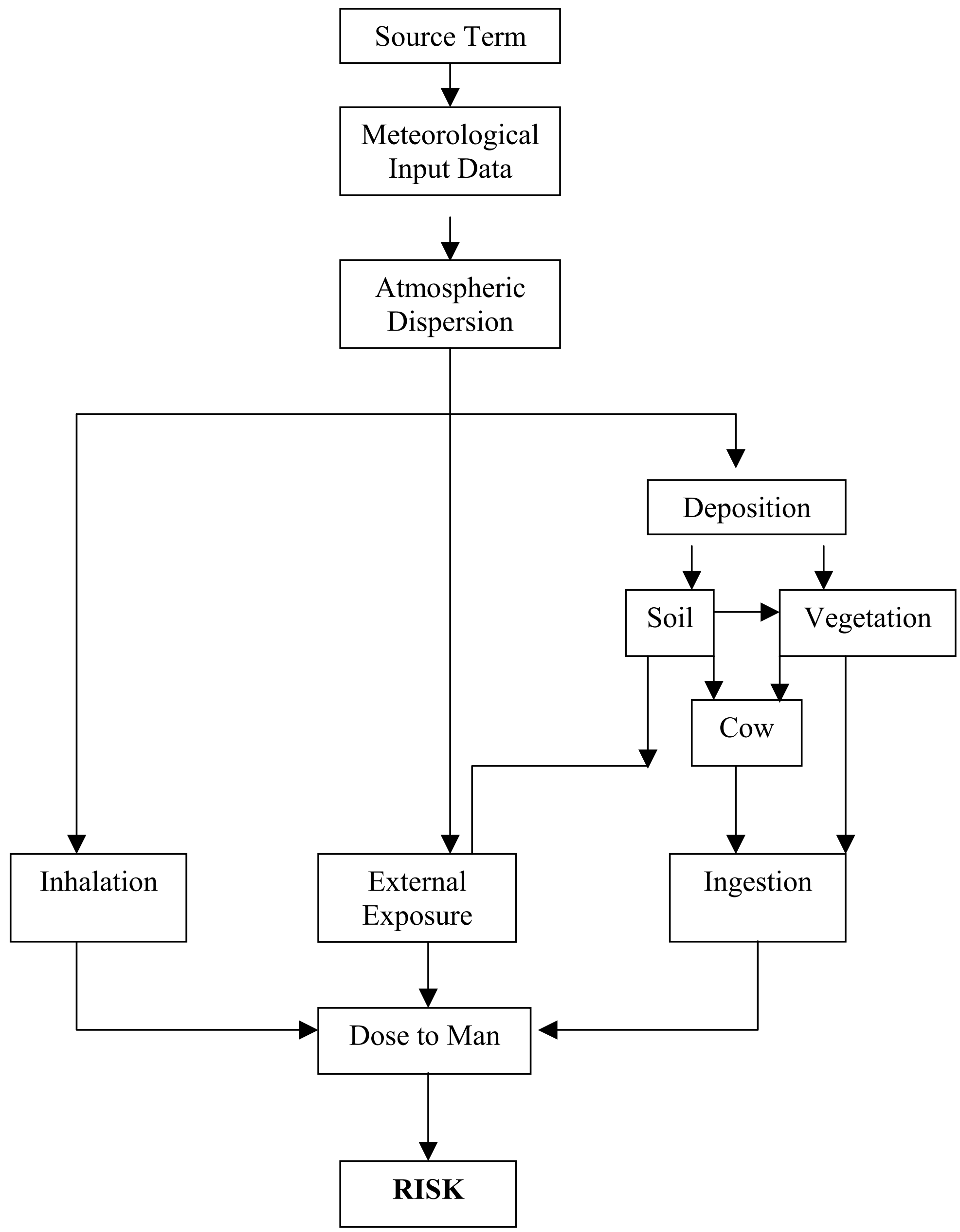


Figure 2.1. Pathways Considered in Exposure Modeling

Slaper (1994) used the exposure assessment model implemented in NucRed computer program in the study assessing risk for accidental releases from nuclear power plants in Europe. The exposure pathways were inhalation, ingestion and external exposure. Figure 2.1 provides a schematic representation of the exposure model used in that study. Dose conversion factors, which express the relationship between concentrations and resultant human doses (Lo, Chen, Huang and Chou, 2000), are used for assessment of the exposure.

The inhalation dose comes from breathing the contaminated air. During the passage of radioactive cloud radionuclides are inhaled. The inhalation dose is calculated for each radionuclide by multiplying the total amount inhaled activity with the dose conversion factor for inhalation for the particular radionuclide. The total inhaled activity is directly proportional to the breathing volume and air concentration. For inhalation the dose factor relates the dose rate to the amount of the radioisotope inhaled

The groundshine dose comes from standing or walking on ground on which radioactive particles have been deposited. For groundshine, the dose factor relates the dose rate to the concentration on the ground.

For cloudshine, the dose factor relates the dose rate to the concentration in the air. The shielding factor accounts for the fact that some of the times the people will be indoors and will be partially shielded by the building.

The first three of these dose pathways result in immediate doses that can cause health effects acute effects. In addition to three pathways that cause acute effects, long term exposure from contaminated ground and ingestion also contributes to delayed health effects (Hasermann, 2000).

2.7.3. Risk

Two definition of the term “risk” is done in IAEA Safety Glossary. Depending on the context, it may be used to represent a quantitative measure (as, for example, in definitions (i) and or as a qualitative concept (as in definition (ii)).

(i) The mathematical mean (expectation value) of an appropriate measure of a specified (usually unwelcome) consequence:

$$R = \sum_i P_i * C_i \qquad \text{Eqn. 2.1.}$$

P_i : Probability of occurrence of scenario or event sequence i.

C_i : Measure of the consequence of that scenario or event sequence.

Typical consequence measures C_i include core damage frequency, the estimated number or probability of health effects, etc. If the number of scenarios or event sequences is large, the summation is replaced by an integral.

(ii) The probability of a specified health effect (deterministic or stochastic) occurring in a person or group as a result of exposure to radiation.

The health effect can be risk of fatal cancer, risk of serious hereditary effects or overall radiation detriment as there is no generally accepted ‘default’. Risk herein is commonly expressed as the product of the probability that exposure will occur and the probability that the exposure, assuming that it occurs, will cause the specified health effect (see subsequent Chapter for details).

Among different risk terms the term "lifetime risk" is explained as the probability that a specified health effect will occur at some time in the future in an individual as a result of radiation exposure (IAEA, 2000).

2.7.4. Health Effects of Radiation:

Human data analyzed for radiation effects and modeling are Japanese survivors for Atomic-bombs, early radiotherapy studies (ankylosing spondydlitis treatments with radiation in 1935-44 in Britain, radiologists practicing prior to 1922, children who received radiotherapy for enlarged thyroid etc.), high doses in early diagnostic work tuberculosis studies using fluoroscopy in Canada and US (Turai, 2000). One of the main reasons for using the atomic bomb survivor data is the clarification of the long-range effects for a wide range of age groups including both men and women. By applying the data from atomic bomb survivors to the data for the Japanese population, it is possible to estimate the lifetime risk of cancer for a given dose of radiation.

International Commission on Radiological Protection (ICRP) examines the published studies and reviews carried out by many bodies like United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and Committee on Biological Effects on Ionizing Radiation (BEIR) and then draw conclusions about quantitative estimates of the consequences of radiation protection. The Commission defines deterministic and stochastic effects such that: As ionising radiation passes thorough the body, it interacts with the tissues transferring energy to cellular and other constituents by ionization of their atoms. If the damage to DNA is slight and the rate of the damage production is not rapid, i.e. at low dose rate, the cell may be able to repair most of the damage. If the damage is irreparable the cell may die either immediately or after several divisions. Rapid and uncompesetable cell death at high doses leads to early deleterious radiation effects which become evident within days or weeks, are known as “deterministic health effects”. Lower doses and dose rates don’t produce these acute early effects, because the available cellular repair mechanisms are able to compensate for the damage. These late effects, cancer induction and hereditary defects are known as “stochastic health effects”. These effects can be more explained below according to the Commission definition.

(i) Deterministic Effects

Deterministic effects occur when the dose is above a given threshold (characteristic for the given effect) and severity increases with the dose (Evans and Moeller, 1998). Many cells must die or have their function altered to mention deterministic effects. These effects are divided into fatal and non-fatal effects. Those non-fatal effects which are transitory and leave no permanent health detriment, such as pulmonary syndrome, hematopoietic syndrome and pre-/neonatal death (Hasemann, 2000). Examples of the fatal effects, which cause early death, are lung function impairment, hypothyroidism and mental retardation. The risk of suffering from these effects following irradiation increases rapidly as the dose increases above a threshold value. In table 2.1 there are indicated some acute effects of radiation with the dose range values of their occurrences and time of death after exposure. (Hobbie , 1997)

Table 2.1 Acute Effects of Radiation

Acute effects	Occurrences within the range of dose	Time of death after the exposure
Cerebrovasculer syndrome	100 Gy	24-48 hrs
Gastrointestinal syndrome	5-12 Gy	Days later
Bone Marrow Death (hematopoietic syndrome)	2.5 –5 Gy	Weeks later

(ii) Stochastic Effects

Stochastic effects don't have any known threshold, may result from alteration in only one or a few cells. Probability of occurrence increases with dose. The principal stochastic health effects are the increased incidence of cancers, both fatal and non-fatal. Their appearance is spread over several decades following an accidental release. Estimates of the radiation-induced incidence of cancers are generally based on the assumptions of a linear dose response function without dose threshold (ICRP-60, 1990).

If the damage caused by radiation occurs in the germ cells, this damage (mutations and aberrations) may be transmitted and become manifest as hereditary disorders in the descendants of the exposed individual. It must be presumed that any non-lethal damage in human germ cells may be further transmitted to subsequent generations. This type of stochastic effect is called "hereditary"(ICRP-60, 1990). Hasermann (2000) defined two modules for calculating the individual and collective risks in the RODOS health effects modeling system. The risk of suffering from deterministic health effects following radiation are modeled in the system using "hazard function" in which the probability of an individual being affected, r, is given by;

$$r = 1 - e^{-H} \qquad \text{Eqn.2.2.}$$

H : Function of dose and dose rate.

H is taken to be two-parameter Weibull function of the form;

$$H = \ln 2\left(\frac{D}{D_{50}}\right)^{V} \qquad \text{Eqn.2.3.}$$

D : Average absorbed dose to the relevant organ

D_{50} : Dose which causes the effect in 50% of the exposed population

V : Shape parameter that characterizes the slope of the dose-risk function.

The risk from suffering stochastic effects (only fatal cancer) is calculated as multiplying the individual effective lifetime dose with an appropriate risk factor in RODOS. The stochastic risk, r is given by;

$$r = eff.dose * riskfactor \qquad \text{Eqn. 2.4.}$$

The calculation of collective risk is also performed in the system as calculating the number of deterministic and stochastic risks respectively, in the population.

Cao, Yeung, Wong, Ehrhardt and Yu (1999) studied the health effects following the accident at Daya nuclear power plant by the model Cosyma. Authors referred to deterministic and stochastic effects as early and late effects, respectively. Cosyma models early effects in a way identical to the RODOS system. However late effects considered include 11 cancers and hereditary effects, which means the modeling is more sophisticated than the RODOS. The cancers included in the study were leukemia, and cancers of bone surface, breast, lung, stomach, colon, liver, pancreas, thyroid, skin and the remainder.

CHAPTER 3

METHODOLOGY

3.1. Methodology Overview

In the previous chapter general information on reactors, accidents, modeling and risk was provided to get the reader acquainted with the topic. The purpose of this chapter is to present methodology used in the modeling and health risk assessment parts of the study.

It should be pointed out from the beginning that since the purpose of this study is to investigate the health risk, the parameters and assumptions are based on the fairly conservative approaches and results represent the highest possible risk that can be induced if accidents occur in either one of the reactors studied.

3.2. The Determination of the Worst Case Accident Scenario

As pointed out in Section 2.3, there are five different types of core damages for the light water reactors (IAEA Tecdoc-955, 1997). Among them, core meltdown accident has been used in this study, since the radiological consequences are larger than other accidents with a higher probability. This accident has been postulated to occur together with early catastrophic failure of the containment for both reactors. When such an accident occurs, all radionuclides in the containment escape to the atmosphere without any reduction in the containment due to natural systems like radioactive decay or engineered safety systems like sprays.

3.3. Source Term Parameters

Since Kozloduy units 1 and 2 are already in shut down status, the accident has been assumed to occur at the older units of Kozloduy, either 3 or 4 which have electrical power generation of 440 MW(t), each. The proposed nuclear power plant at Akkuyu has been assumed with a electrical power of 1000 MW(t), which is the suggested design value. The core inventory of the 440 MW(t) reactor is directly proportional to its electrical power and calculated from the inventory based on the 1000 MW(t) electrical power (Slaper,1994). The core inventories of both Kozloduy and Akkuyu reactors are given in Appendix B; Table B.1.

The release fractions for the radioactive elements in the core taken into account in the case of the core meltdown accident with the fuel cladding temperature above 1650 ˚C are listed in Table 3.1. These fractions are based on IAEA Tecdoc -955 (1997) and used for both reactors. The whole volume of the containment is assumed to release to the atmosphere in one hour in the case of early catastrophic failure of the containment. One-hour duration of the accident is typical in these types of worst-case scenarios and is frequently used in literature (IAEA Tecdoc-955, 1997). The reduction in airborne radioactivity in the containment by natural processes and containment spray systems or the other engineered safety features are not taken into account because (1) they will not have a chance to operate in the case of an early failure of the containment and (2) such measures are very limited in Kozloduy NPP.

Table 3.1. PWR Core Inventory Fractions Released to the Containment

Group	Core Release Fraction
Noble gas (Xe, Kr)	0,95
Halogens (I)	0,35
Alkali metals (Cs, Rb)	0,25
Tellerium metals (Te, Sb)	0,15
(Ba)	0,04
(Sr)	0,03
Cerium Group (Ce, Np, Pu)	0,01
Ruthenium group (Ru, Mo, Tc, Rh)	0,008
Lanthanium group (La, Y, Zr, Nd, Nb, Pr,)	0,002

The form of radioisotopes that are released to the atmosphere is important in subsequent transport studies. The forms of isotopes used in this study are based on reports from NRC (Nuclear Regulatory Commission), an organization that regulates the US commercial nuclear power plants and the civilian use of nuclear materials. The NRC developed accident scenarios for evaluating the radiological consequences of a light water reactor loss of coolant accident. The forms of radioisotopes used in this study were obtained from an NRC accident scenario that involves loss of coolant water in a light water reactor (US NRC Reg.Guide 1.183, 2000).

Based on the NRC values, 95% of the radioiodine released from the reactor coolant system to the containment is assumed to be cesium iodide (CsI), 4.85% elemental iodine, and 0.15% organic iodide. With the exception of noble gases, elemental and organic iodine fission products were assumed to be in particulate form.

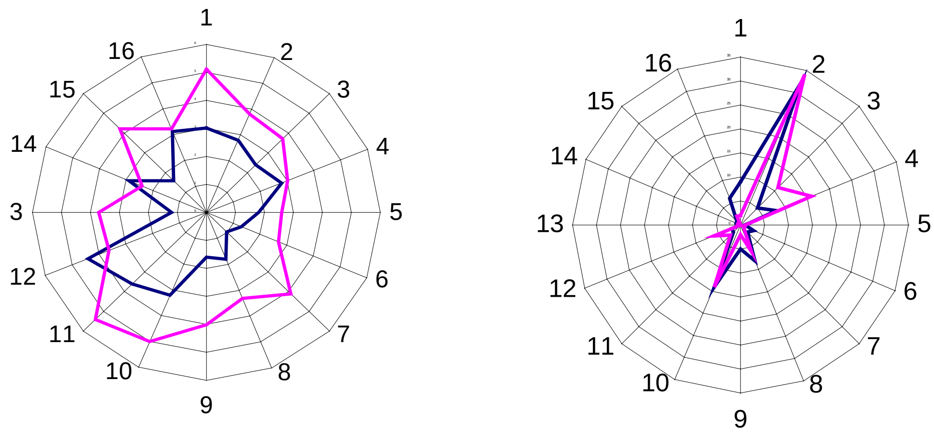
The core inventories of both reactors for each radionuclide given in Table B.1 of Appendix B were multiplied with the fractions in Table 3.1., and used together with other source term parameters, namely the release duration and release height, in the atmospheric dispersion model HySPLIT.

Release height is another important source term parameter and is used in HySPLIT. The release height is important for subsequent dispersion modeling. It is known from the Chernobyl accident that heat from the initial steam explosion and subsequent graphite fire lifted a cloud of radioactive particulates at least one kilometer up into the atmosphere. Though graphite fire is specific to Chernobyl type reactors, it is also known from the literature that, the high altitude release between 700-1700 m is possible for a severe accident at the Kola, the Arctic nuclear power plant (Baklanov and Serensen, 2000). Plume height values that ranges between 700 m and 2000 m seemed realistic in both Kozloduy and Akkuyu plants. Emissions to high levels in the atmosphere would lead to maller deposition over Turkey. Since the worst-case scenario is being developed in this study, 800 m plume rise, which is close to lower end of the range, was used in the transport modeling.

3.4. The Selection of the Meteorological Year

Since it is not known beforehand what the weather conditions will be the arbitrarily selected year 2000 was used for modeling of the atmospheric dispersion process after verifying its representativeness for long years. The data from meteorological stations at İpsala, Çorlu are used for the verification instead of that of Bulgaria due to the short distances between our stations and Bulgaria boundary. Since this study investigates the health risk due to the airborne radioactivity following the nuclear accident the most important meteorological parameters are the wind related parameters. So the data compared are wind speed and the wind blowing frequency of year 2000 and long years. It seems there is not much difference them. The graphs are shown in Figure 3.1 and 3.2. for the İpsala and Çorlu stations, respectively.

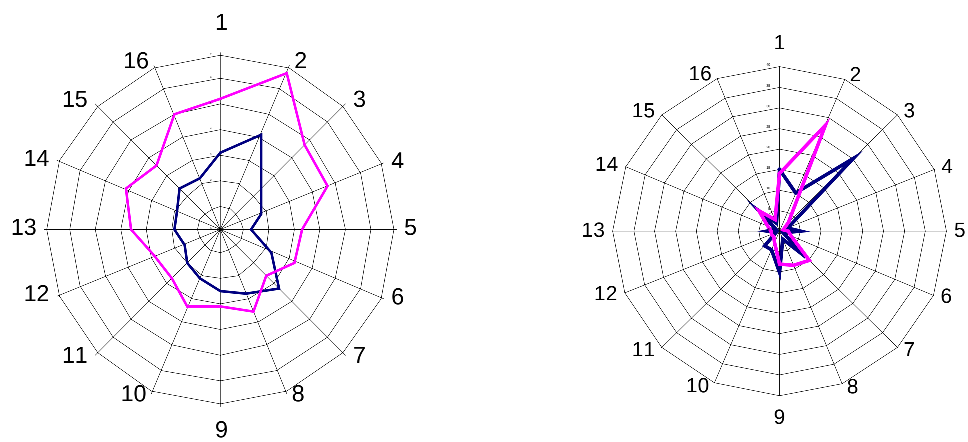
The meteorological data of the year 2000 used in the modeling was taken from NCEP's FNL achieve (already explained in Section 2.5.1).



Wind Speed

Wind Frequency

Figure 3.1 İpsala Station-The comparison of wind blowing frequency and speed for long years and 2000



Wind Speed

Wind Frequency

Figure 3.2. Çorlu Station-The comparison of wind blowing frequency and speed for long years and 2000.

3.5. Other Model Input Parameters Used in the Study

Calculation of dry deposition is one of the most sensitive and most uncertain areas, not only in the modeling of radioactivity, but also the in modeling of all types of pollutants, because dry deposition is sensitive for interaction between the modeled parameter (in our case isotopes) and the ground cover, which changes in time and space.

Dry deposition calculations in the model (HySPLIT) were performed using "*dry deposition velocity*" approach. In this approach, the deposition flux is assumed to be equal to the multiplication of surface concentration of isotopes and dry deposition velocity (v_d). Surface concentrations are calculated by the model and are assumed to be correct. The critical parameter is the v_d, which differs from one isotope to another based on their interaction with the surface. There is an inherent uncertainty in all synoptic models that arises from the value of v_d used. In most models only one v_d value can be used for each pollutant (or isotope). However, deposition velocity for modeled parameter changes with the type of the ground cover, as it depends on interaction between parameter and surface. Since very large areas are involved in synoptic models ground cover shows substantial variations in the model domain.

Dry deposition velocity can be either set directly for the radionuclides classed according to their physical-chemical form or can be calculated using resistance method which requires information on the parameters that describe interaction of radionuclides with the surface, such as molecular weight, surface reactivity, diffusivity, effective Henry's constant etc.

The constant dry deposition approach is used in this study with all due uncertainties. Although, constant dry deposition velocity approach is the most uncertain one, it is the most widely used one in synoptic models (Baklanov and Serensen, 2000), because surface resistance approach involves fairly extensive calculations that have to be repeated for different surface cover type.

In this study, dry deposition velocity is assumed to be a constant for each radionuclide and surface type. Dry deposition values reported in literature (Baklanov and Serensen, 2000) for different surface types and for different isotope groups are given in Table 3.2, to demonstrate the variability of the value. Since Turkey is mostly covered by the agricultural areas (among surface types given in Table 3.2) the v_d values for agricultural surface type were used in our simulations. In this study deposition over seawater wasn't taken into account, as the objective is to calculate health risk.

Table 3.2. Dry Deposition Velocities (m s^{-1}) for Various Surface Types

Physical-Chemical form	Water	Grass	Agricultural	Forest	Urban
Noble gases	0	0	0	0	0
Aerosols	0.0007	0.0015	0.002	0.0075	0.0005
Elemental Iodine	0.001	0.015	0.02	0.073	0.005
Organically bound iodine	0.0005	0.00015	0.0002	0.00075	0.00005

The wet deposition is calculated by separate handling of in-cloud and below-cloud processes. In cloud processes involve incorporation of radioisotopes into clouds and subsequent transport to Turkey and below cloud processes involve washing of radioisotopes by falling hydrometeors. There are two important parameters in wet deposition of isotopes. For isotopes that are in particulate form the efficiencies with which they are incorporated into clouds or into rain droplets. The values for in-cloud efficiency and below cloud capture rate were obtained from studies performed in the NOAA, Air Resources Laboratory (Draxler and Hess,1997). The values used for in-cloud and below-cloud capture efficiencies in the model are $3.2x10^5$ and $5.0x10^{-5}$ s^{-1}, respectively

The fraction of gaseous isotopes that are captured by cloud and rain droplets is determined by their solubility in water. Hence the Henry's Law constant is an important parameter for gaseous isotopes. It should be noted that the only isotopes that are modeled in the gas phase are noble gases, organic and elemental iodine.

In most of the studies in the literature it is clearly demonstrated that noble gases do not dry and wet deposit to the surface and they are removed from the atmosphere only by decay process (Pasler 2000; Baklanov and Serensen 2000). Based on these literatures the Henry's Law constant (as well as dry deposition velocities) of noble gases was set to "0" in our model simulations. This means that health effects of noble gases are associated with inhalation of isotopes that exists in the atmosphere and is not affected by inhalation of resuspended material that is deposited to surfaces.

Henry's Law constant for organic iodine was obtained from Chernfinder (2001) which is 0.00526 atm-cum/mol. This value was then converted to 0.19 M/atm that is the unit used by the model. However no data for elemental iodine could be obtained from the literature and it was calculated using the solubility and vapor pressure values provided by Chernfinder (2001) as $3.09x10^{-4}$ atm-cum/mol using the following relation and converted as 3.24 M/atm;

$$HLC = \frac{(VP)(MW)}{S} \qquad \text{Eqn.3.1}$$

HLC : Henry's Law constant ($atmm^3 mol^{-1}$)
MW : Molecular weight; (253.809 g mol^{-1})
VP : Vapor pressure at 25 ˚C; (0.305 mmHg)
S : Solubility in water at 25 ˚C ; (330 mgl^{-1})

The effect of radioactive decay is treated simultaneously for the whole group of radionuclides in the formulation of radioactive chains when the daughter radionuclides are borne and will grow in the plume with a decay of the parent radionuclides. Variations of deposition parameters with the formation of new isotopes following radioactive decay cannot, however, be modeled and the values of dry deposition and washout coefficient should reflect the contents of the initial radioisotope inventory.

Isotopes that are dry or wet deposited to the surface can be resuspended if the winds are strong enough and resuspended radioactivity can be inhaled like the isotopes that exist in the atmosphere. The resuspension process is included in the model, but it requires a resuspension rate to calculate the amount of surface material that is resuspended and available for inhalation. Most of the data for resuspension rate involved studies after Chernobyl accident. The resuspension rate used in this study is 1.0×10^{-6} m^{-1} and obtained from the study of Fogh et al. 1998.

Particles and gases were modeled in another (different) way in terms of their density, shape and diameter. Draxler (1997) stated that if any of these values is set 0, the model treats the pollutant as gas. That of the particles are recommended to set as unity by Draxler (1997). Kinser (2001) who studied wet deposition of Cs-137 after

Chernobyl accident and effects of both in-cloud and below-clouds parameters on total deposition used unity for its density, shape and diameter values. The values of these parameters were set as unity for particles and zero for gases following Draxler and Kinser's approaches.

The values of the parameters described herein, are presented in Chapter 4 along with the results of the study.

3.6. Radiation Dose Assessment Methodology

The atmospheric dispersion and deposition modeling of radionuclides provided above was applied to estimate the doses due to passage of a contaminated cloud and deposition of radionuclides. The exposure assessment methodology herein is the same with those used by Slaper (1994), which is implemented in NucRed computer program developed at RIVM in Bilthoven, Netherlands. All formulations unless referencing to others were taken from this literature study. The methodology used to calculate doses via inhalation, ingestion and external exposure are the same with the methods developed to evaluate the radiological consequences of the Chernobyl accident (UNSCEAR, 1988). The dose conversion factors used for the calculations are obtained from Nosske (1985) and Kocher (1983). Brief explanations of these methods are presented in the following paragraphs.

The dose following the accident was calculated over a period of 70 years, in other words the accumulated lifetime dose commitment was calculated. The countermeasures to reduce the exposure were not considered. Doses were computed for adults to give a good representation for the overall population at the selected receptor grids. Exposure due to immersion in the contaminated air, breathing the contaminated air, radioactive material deposited on the ground, and drinking and eating food contaminated by deposited radioactive particles are taken into account for calculations.

The days in which both the radionuclide concentration in air and deposition on ground were maximum were referred as worst days. Studies after the Chernobyl accident have demonstrated that ingestion pathway produced a major contribution to the committed dose (Slaper, 1994). Since radiation dose is received by ingestion pathway as a result of the deposition of radioactivity on ground, a single worst day was taken into account as a worst deposited day and the exposure assessment was performed based on this day. However in order to take into account the air concentrations of radionuclides in the dose calculations, maximum daily air concentration through the 15-day simulation period starting on day which caused the worst deposited day at the end of it was used.

The most populated cities in each region of Turkey together with the highest deposited grit of each accident were selected as the receptor points for the exposure and risk calculations. Twelve cities selected over Turkey include İstanbul, Balıkesir, İzmir, Manisa, Samsun, Kocaeli, Ankara, Konya, Şanlıurfa, Erzurum, Adana and Antalya.

The deposition, concentration and time-integrated concentration of the all radionucleides were calculated for each grid over Turkey. The radioactivities for the selected cities were obtained by interpolation of activities at the four neighboring girds. The area of each grid used in this study (1˚x1˚) is 111x85 km^2. The activity values that deposit over the actual areas of the cities were calculated by simple proportionality.

3.6.1. Inhalation Pathway

The dose acquired by inhalation (of both radionucleides that existed in the atmosphere and resuspended deposited isotopes) was calculated using the following relation.

$$D_{inh} = CA * VB * DC_{inh} * (1 - F_{ind} + F_{ind} * r_{ind}) \qquad \text{Eqn.3.2}$$

D_{inh} : Total inhalation dose (Sv),

CA : Time integrated air concentration (Bq.m^{-3} day),

VB : Breathing rate (23 m^{3}day^{-1}) (ICRP-23),

DC_{inh} : Radionuclide specific dose conversion factor for inhalation (Sv Bq^{-1}) (the values are presented in Appendix B; Table B.2),

f_{ind} : Fraction of time spent indoors (the value of 0.7 is used by Slaper,1994)

r_{ind} : Reduction factor for indoor air concentration.

In this study the indoor concentrations of isotopes are assumed to be identical with the outdoor concentrations. Most of the studies performed on indoor air pollution demonstrated that concentrations of pollutants are higher in indoor air if there are indoor sources for them. However, for pollutants that originate only from outdoor sources, indoor concentrations are equal to or smaller than outdoor concentrations. Since there are no indoor sources for radioactive material, indoor activities are expected to equal to or smaller than outdoor activities. In this study indoor concentrations of isotopes are assumed to be identical with outdoor concentrations, because there is no consensus in the literature on how much smaller indoor activities will be, or if they will be smaller.

3.6.2.Ingestion Pathway

Five major food categories are distinguished in ingestion modeling: vegetables, cereals, roots, tubers, and milk and meat from cows. Exposure through drinking water is not included in the ingestion pathway, because most of the studies demonstrated that activity acquired through drinking is insignificant (Slaper,1994). The concentration of plants due to uptake from the soil is considered to be directly proportional to the soil concentration (Simmonds et al., 1987; Blaauboer et al., 1992). Time-integrated concentrations of isotopes in soil over the evaluation period of 70 years were calculated using the following expression;

$$C_s = \frac{OA}{S*(\lambda + \lambda_1)}(1 - e^{-(\lambda+\lambda_1)*tend}) \qquad \text{Eqn. 3.3}$$

C_s : Time integrated dry soil concentration (Bq kg^{-1} day)

OA : Total deposition at the end of 15-day simulation per unit area (Bq m^{-2})

S : Mass of soil in plough layer per unit area ($kg.m^{-2}$, calculated multiplying depth of plough layer (m) and with soil density ($kg.m^{-3}$; Appendix B; Table B.5),

λ : Physical decay constant for radionuclide considered (day^{-1}; Appendix B; Table B.2)

λ_1 : Constant describing removal from plough layer (day^{-1})

t_{end} : End of the evaluation period (70 years).

The constant describing the removal of radionuclides from soil is calculated using the relation;

$$\lambda_1 = \frac{W_R + W_I - W_E}{\theta * h * (1 + \frac{K_d * \rho}{\theta})} \qquad \text{Eqn.3.4.}$$

(W_R+W_I+W_E): Water balance, which consist of rainfall (R) plus irrigation (I) minus loss due to evaporation (E) (m day^{-1}; Appendix B; Table B.5)

θ : Volumetric water content of soil (dimensionless; 0.25 is used; Appendix B; Table B.5)

h : Thickness of plough layer (m; Appendix B; Table B.5)

K_d : Soil affinity of radionuclide (m^3 kg; Appendix B; Table B.4)

ρ : Soil density (kg m^3; Appendix B; Table B.5)

Since the time period in which isotopes deposit onto plants are much shorter than the growth period of crops, average contamination during the growth is considered. Radionucleide concentration in plants is directly proportional to deposition and calculated by;

$$Cp = \frac{OA * F_{ip} * (1 - e^{-(\lambda + \lambda w) * tap}}{Y_p * (\lambda + \lambda_w)} + C_s * B_v \qquad \text{Eqn.3.5.}$$

Cp : Radionuclide concentration in plants; time integrated (Bqkg^{-1} day)

OA : Total deposition per unit area (Bqm^{-2}),

F_{ip} : Direct interception fraction for crop type p (Appendix B; Table B.4)

λ : Physical decay constant for radionuclide considered (day^{-1} Appendix B; Table B.2),

λ_w : Rate constant for the reduction of the concentration of the material deposited on the surface of the vegetation due to processes other than radiological decay (day^{-1}; Appendix B; Table B.5)

t_{ap}: Time period during the growing season that crops can be contaminated through direct interception of deposition (day; Appendix B; Table B.5)

Y_p : Agricultural productivity (yield) or standing crop biomass of the edible portion of vegetation (kg m^{-2}; Appendix B; Table B.5)

C_s : Time integrated concentration of radionuclides in (dry) soil (Bqkg^{-1}day)

B_v : Concentration factor for uptake of the radionuclide from soil by edible parts of crops (Bq kg^{-1} plant tissue per Bq dry soil; Appendix B; Table B.4)

Although vegetables, root crops and tubers, and gray contribute directly to human ingestion grass contributes indirectly to ingestion via contamination of cow-milk and meat. The contamination of cow-milk is calculated using the following relation (Slaper,1994);

$$C_{milk} = F_{milk} * (I_{cow,grass} * C_{grass} + I_{cow,soil} * C_s) \quad \text{Eqn.3.6.}$$

C_{milk} : Time integrated concentration in cow milk (Bqkg^{-1} day)

F_{milk} : Transfer to milk (daykg^{-1};Appendix B; Table B.4)

$I_{cow,grass}$: Grass intake for cow (kgday^{-1}; Appendix B; Table B.6)

C_{grass} : Time integrated radionuclide concentration in grass, per kg fresh weight (Bqkg^{-1}day)

$I_{cow,soil}$: Soil intake for cow (kg day^{-1}; Appendix B; Table B.6)

C_s : Time integrated dry soil concentration (Bqkg^{-1}day)

Replacing the milk index by meat the same equation is also applied to calculate the concentration in cow meat.

The overall human ingestion is calculated by using the following relation;

$$A_I = \sum_{p=1}^{5} (I_p * F_{b,p} * C_p * e^{-\lambda * td}) \quad \text{Eqn.3.7.}$$

A_I : Total intake of specific radionuclide (Bq)

I_p : Human intake of food product p (kgday^{-1}; Appendix B; Table B.6)

$F_{b,p}$: Reduction factor for removal of radionuclides due to food preparation process (Appendix B; Table B.6)

C_p : Time integrated concentration in food product p, just after harvesting/milking/slaughtering prior to food preparation ($Bqkg^{-1}day$)

λ : Physical decay constant for radionuclide considered (day^{-1} Appendix B; Table B.2)

t_d : Time between harvesting/milking/slaughtering and consumption (day; Appendix B; Table B.6)

Finally, total dose acquired by humans via ingestion is determined using the following relation;

$$D_{ing} = DC_{ing} * A_I \qquad \text{Eqn.3.8.}$$

D_{ing} : Total ingestion dose for the specific radionuclide (Sv)

DC_{ing}: Radionuclide specific dose conversion factor for ingestion ($SvBq^{-1}$; Appendix B; Table B.2)

A_I : Total intake of specific radionuclide (Bq).

3.6.3. External Exposure Pathway

The radioactivity in air can also directly affect population even if they do not inhale it or ingest food contaminated by isotopes. This is referred to as external exposure and it can occur through exposure to the radioactive cloud or exposure to the activity deposited onto surfaces. Both of these pathways are included in the total dose acquired by humans. The relationships derived in literature were used in calculations of external dose.

(i) External exposure from radioactive cloud

The effective dose due to external exposure from the cloud is calculated using the following relation;

$$D_{extcl} = C_A * DC_{extcl} * (1 - F_{ind} + F_{ind} * F_{buildcl}) \quad \text{Eqn.3.9.}$$

D_{excl} : Dose due to external radiation exposure from cloud for specific radionuclide (Sv)

CA : Air concentration for specific radionuclide ($Bqsm^{-3}$)

$DC_{extcl:}$ Dose conversion factor for unit air concentration with specific radionuclide for external radiation dose from infinite cloud ($Svs^{-1}Bq^{-1}m^{3}$; Appendix B; Table B.2.)

F_{ind} : Time averaged fraction of time spent indoors (0.7 is used by Slaper, 1994)

$F_{buildcl}$: Average indoor reduction factor of external radiation from clouds (0.7 is used).

(ii) External exposure from deposited radioactivity

The external radiation dose due to isotopes deposited over the ground and surfaces around humans is calculated for three separate time intervals:

The first month following deposition

The period between the first month and one year following the deposition

The period after one year until the end of 70 years.

During the first month following deposition the external dose is calculated assuming a surface contamination and shielding due to buildings is considered for the time spent indoors. The modeling for the period after one month is similar, however two additional multiplication factors are introduced, describing shielding of radiation due to penetration in the ground, and the reduction of surface contamination in urban areas due to runoff. UNSCEAR (1988) concluded that approximately 50% of the deposited radionuclides were lost with a half-life of 7 days. The approach followed here allows for a 50% reduction after one month. The external dose from deposited activity is calculated using the following relation;

$$D_{extgr} = DC_{extgr} * OA * \left[1 - F_{ind} * (1 - F_{build})\right] * \frac{e^{-\lambda * t_{i-1}} - e^{-\lambda * t_i}}{\lambda} * F_{runoffi} * F_{penei} \qquad \text{Eqn.3.10}$$

D_{extgr} : Dose (Sv) due to external exposure from a specific radionuclide deposited on the ground in period i: three periods are considered

DC_{extgr} : Dose conversion factor for external exposure from surface contamination for a specific radionuclide, when no shielding occurs ($Svs^{-1}Bq^{-1}m^2$; Appendix B; Table B.2.)

OA : Total deposition for specific radionuclide per unit area (Bqm^{-2})

F_{ind} : Fraction of time spent indoors (0.7 is used)

F_{build} : Reduction factor for shielding inside building (0.3 is used)

$F_{runoffi:}$ Correction for runoff in urban areas (the term is explained in subsequent paragraphs). The runoff correction factor used in this study is 1 in the first month at urban areas and also 1 for rural areas
F_{penei} : Shielding factor due to penetration of radionuclides in the ground, this factor is 1 during the first month, 0.5 in the period between one month and one year, and 0.37 after 1 year

t_{i-1}, t_i : Time at start and end of period I, respectively.

The correction for runoff was calculated applying;

$$F_{runoffi} = 1 - F_{popurban} * (1 - F_{urbani}) \qquad \text{Eqn.3.11}$$

$f_{popurban}$: Fraction of population living in urban areas

f_{urbani} : Fraction of contamination runoff in urban areas (0.5 after first month)

Fraction of population living in urban areas was calculated using the census results for 2000 provided from State Statistical Institute. Those for the grit area with the maximum deposition was calculated considering the cities within the grit as a single city in which the fraction of population living in urban areas was found by summation of population living in the urban areas divided by total population in the cities. The values of $f_{popurban}$ are listed in Appendix B, Tables B.7 and B.8.

Doses to an individual are converted to population doses using population data based on the census results for 2000 provided from State Statistical Institute for the receptor grids chosen, which are given in Appendix B; Tables B.7 and B.8.

3.6.4. Correction Factors Used in Exposure Assessment

The formulations of exposure assessment methodology don't include effects of daughter radionuclides. For 16 of the major nuclides a correction was included to allow for the doses due to ingestion of the daughter nuclides. The corrections were used as multiplicative ingestion correction factors; ingestion dose was multiplied with this correction factor. The correction factors are obtained from Kirchner (1990) and listed in Appendix B; Table B.3. In addition 11 radionuclides, strong gamma emitters, with sufficiently short living daughters contribute to external exposure. The external dose conversion factor was increased with the dose conversion factor of the daughter. In studies reported in the literature, correction factor were not applied to inhalation pathway (Slaper, 1994). However, most of these are studies performed close to the accident site and it is understandable that activity due to daughter nuclides are small compared to activity due to parent nuclides. In this study air masses that carry radioactivity reaches to Turkey after a finite period of time and activities due to daughters may not be negligible.

The contribution of daughter nuclide doses to the total dose acquired by humans was tested with a sensitivity study. The results demonstrated that the effects of the daughter nuclides caused an overall increase in dose of less than 2% considering all pathways, the corrections related to the inhalation pathway was neglected in this study, as well.

3.7. Health Risk Assessment Methodology

Deterministic and stochastic health effects of radiation were described in Chapter 2.7.4. Only stochastic (late) effects for the accidents postulated to occur at both reactors were investigated in this study. The acute effects of accidents, that is to say the mortality and health risk that occurs immediately after the accident and in the close proximity of the accident site is not included in discussions.

The following fairly simple relation, used by Hasemann (2000) for calculating the individual stochastic risk in the RODOS health effects modeling system is used in the study;

$$r = eff.dose * riskfactor \qquad \text{Eqn.3.12.}$$

The effective dose in this relation is calculated as described in previous sections. The risk factor is obtained from literature. For the risk factor, the value of 502 is recommended by Paretzke (1990). The risk factor is expressed in terms of the number of fatal cancers per million people for a single exposure of 10^{-2} Sv, assuming the age structure and natural cancer incidence of the German population. After transforming it to an individual risk factor and individual dose of 1 Sv, the default value of $5x10^{-2}$ is used in RODOS modeling system (Hasemann, 2000). This value is same as those recommended by ICRP for fatal cancer (ICRP-60,1990) (see Table

3.3). Slaper (1994) used the value of $2.5x10^{-2}$ per Sv in his stochastic risk calculations.

The value recommended by ICRP-60 (1990) and used by Paretzke (1990) was applied in this study to determine stochastic risk. The risk factors for fatal, non-fatal and hereditary effects of radiation used in this study are given in Table 3.3. Fatal, non-fatal and hereditary effects were calculated by multiplying the accumulated lifetime dose commitment and coefficients that are given in this table.

Table 3.3. Nominal Probability Coefficients for Stochastic Effects (Sv^{-1})

Exposed Population	Fatal cancer	Non-fatal cancer	Severe hereditary effects
Whole Population	$5.0x10^{-2}$	$1.0x10^{-2}$	$1.3x10^{-2}$

3.8. Determination of Simulation Period

The model was run assuming the release of Cs-137 from Kozloduy for the arbitrarily selected day of January 23, 2000 and the other following input data to determine the simulation period. The graph showing deposited activity of the radioisotope on Turkey versus time is demonstrated in Figure 3.3.

As understood from this figure, Cs-137 radioactivity has increased for 4 days, and then remained constant for long period because of its long half-life.

Based on this sensitivity run and considering that radionuclides may not release towards Turkey due to direction of the wind speed for short run period the simulation period for the accidental release of the all radionuclides were set 15 days.

Table 3.4. The Values of HySPLIT Input Data For the Sensitivity Run to Determine Simulation Period

	Cs-137
The Starting time (yy mm dd hh)	00 01 23 00 00
The number of the starting locations (lat., lon., m above ground level)	1 43.75 N 23.63 E 10 m
Total run time (hrs)	168
Direction	forward
Top of model (m)	5000
Vertical	Isentropic
Set up meteorological files	Fnl.jan00.002
Identification	C137
Emission rate (Bq/hr)	6.65E+14
Hrs of emission (hrs)	24
Release start (yy mm dd hh min)	00 01 23 00 00
Center (lat. lon.)	39 N 33 E
Spacing (lat. lon.)	1 1
Span (lat. lon.)	7 11
Output grid directory	./
Output grid filename	cdump
Number of vertical levels	1
Height of the levels (m)	0
Sampling start (yy mm dd hh min)	00 00 00 00
Sampling stop (yy mm dd hh min)	00 00 00 00
Interval (hrs)	00 24 00
Particle diameter, density, shape	1 1 1
Velocity (m/s), mol.wght (g), A-ratio, D-ratio, Henry	0.002 0 0 0 0
Henry's(M/a), In-cloud (l/l), below-cloud (1/s)	0 3.2E+05 5.0E-05
Radioactive decay half life (days)	10976
Pollutant resuspension factor (1/m)	0

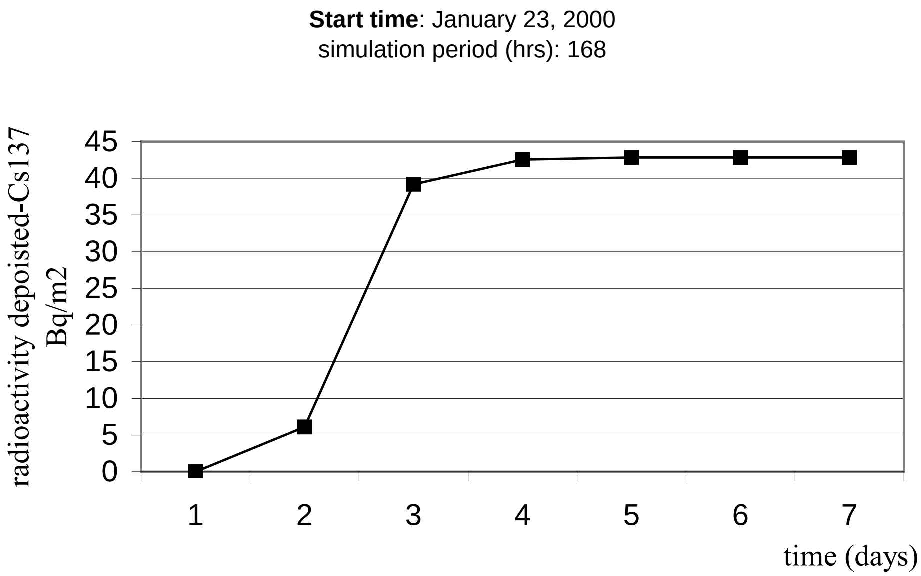


Figure 3.3. Deposited Radioactivity of Cs-137 on Turkey as a Function of Time

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Summary of Model Simulations

The exposure of population in Turkey to isotopes from accidents can occur either through inhalation of airborne radionuclide in the atmosphere or inhalation of isotopes that are first deposited to the ground and then resuspended by the wind action (plus, of course, other routes such as ingestion of contaminated food, drinking contaminated water etc). Consequently, in order to determine how much radioactivity the population is exposed, the model must calculate both atmospheric concentrations and deposition of isotopes. Since 365 runs were performed to determine the highest possible exposure of population from each of the selected power plants (total number of runs is 730), repeating the runs after any modification in the model would cost too much computer time.

The modeling part of the study was performed in three phases. The first phase is tentatively named as initial runs. Initial runs were performed for every day in the year 2000 separately for both power plants. In these runs, an accident is assumed to occur at 12:00 am and model is allowed to calculate deposition and ground level concentrations of isotopes in every grid over Turkey for 15 days.

This procedure was repeated for every day for the year 2000. Kozloduy runs were first performed, and then runs were repeated for the proposed Akkuyu Power Plant.

Although there are more than 60 isotopes that can have health effects on the population, only Cs-137 and I-131 were used in the first part of model simulations (initial runs). Cesium-137 is a typical radionuclide to represent long-lived isotopes ($t_{1/2}$ = 30.1 years) and I-131 was used to represent short live isotopes ($t_{1/2}$ = 8.065 days) emitted from the power plants investigated. The purpose of these runs was not to determine the actual radioactivity deposited over Turkey, but to determine the day in which an accident would result in the highest deposition and ground level concentrations over the country (worst day).

In the second phase, several sensitivity runs were performed for the worst deposited days, with again limited number of isotopes, to determine how different source term parameters affect the ground level activities and deposition.

Finally, actual activities occurred over the grids in Turkey were determined with one run for each power plant. These runs were performed starting at the worst days for each power plant, again model is allowed to do calculations for 15 days; however this time not only Cs-137 and I-131, but also all 64 isotopes that have radiological consequences are included in the simulations.

The exposure and health effects of the potential accidents in each of the selected power plants were determined based on the results of these final runs with host of isotopes.

4.2 The Results of Initial Runs

As pointed out in the previous section, initial runs refer to the 365 model runs performed for each reactor with long-lived Cs-137 and short-lived I-131 isotopes to determine the day of accident that results in the highest deposition and ground level concentrations on the grids in Turkey (the so called worst day). Organic, elemental and particulate forms of I-131 are separately included in these runs as their physical form and deposition fluxes are not the same.

The worst day for each nuclear power plant is calculated (i) for I-131 activity alone, (ii) for Cs-137 activity alone and (iii) for the sum of Cs-137 and I -131 activities.

The simulations have shown that for the Kozloduy NPP, an accident that occurred April 7, 2000 resulted in the highest total activity deposition over Turkey compared to accidents that occurred in all other days of the year 2000. In this particular accident the maximum Cs-137 + I-131 deposition was $2.1x10^6$ Bq m^{-2} in the grid that roughly corresponds to The Marmara Region. The development of the plume after the accident and its gradual transport to different parts in Turkey are depicted in Figure 4.1.

Since the Kozloduy plant is close to Turkish border, The Plume reaches Trakya and Marmara regions within the first day. As expected, very high activity is observed in the plant site where accident occurred ($1.0x10^4$ Bq m^{-3}). The activities reaching to Turkey in the first day of accident are also very high ranging between 10 and 1000 Bq m^{-3}. The area covered in Turkey indicates the zone where actions have to be taken within 24 hrs. In the second day, radioactive plume is observed on the half of the country. The activities expected to be observed ranges between 10 and 10^{-2} Bq m^{-3}. Since very high activities are generated by the short-lived isotope (in initial runs it is I-131), the airborne activity is expected to decrease rapidly in the following days. For example, the difference between the highest activities calculated in the first and second days is approximately three orders-of-magnitude. The airborne activities continue to decrease but not at the same rate.

The highest activities are expected to be in the Marmara and Aegean region, but all Anatolia to the north of Ankara are affected by activities ranging between 10 – 0.01 Bq m^{-3}.

In the third day the part of the plume, which is most radioactive, has passed through Turkey and is located over the Mediterranean Sea, but Turkey, particularly southern parts are under the influence of radioactivity. It should also be noted that, if the plume continued to move south, eastern parts of Turkey would not be affected from the accident. Also the region to the NW of Istanbul is already outside the radioactive plume.

In the fourth day, most active part of the plume is located over Egypt and highest activities in the plume dropped from 10^4 Bq m^{-3} in the first day to 1.0 Bq m^{-3} in the fourth day. The most critical meteorological change that caused this particular run to be the worst one happened in this fourth day. That change is the northerly change in upper atmospheric winds. This change in wind direction in the 1000 m level dispersed the plume (which was about to exit from the country) to north. With this change in transport pattern the radioactive plume covers most of Turkey.

In the following days, northerly movements in upper atmosphere moved the radioactive cloud up to 45 N latitude and east-west oscillations in the winds generated an affect zone extending from Italy on the west and Caspian Sea on the east. It should be noted that in all 15 days of calculations, Turkey remained in the most active part of the radioactive cloud. Airborne activity in the most active part of the cloud decreased to 0.02 Bq m^{-3} at the end of 15-day period (it was 10^4 Bq m^{-3}) in the first day.

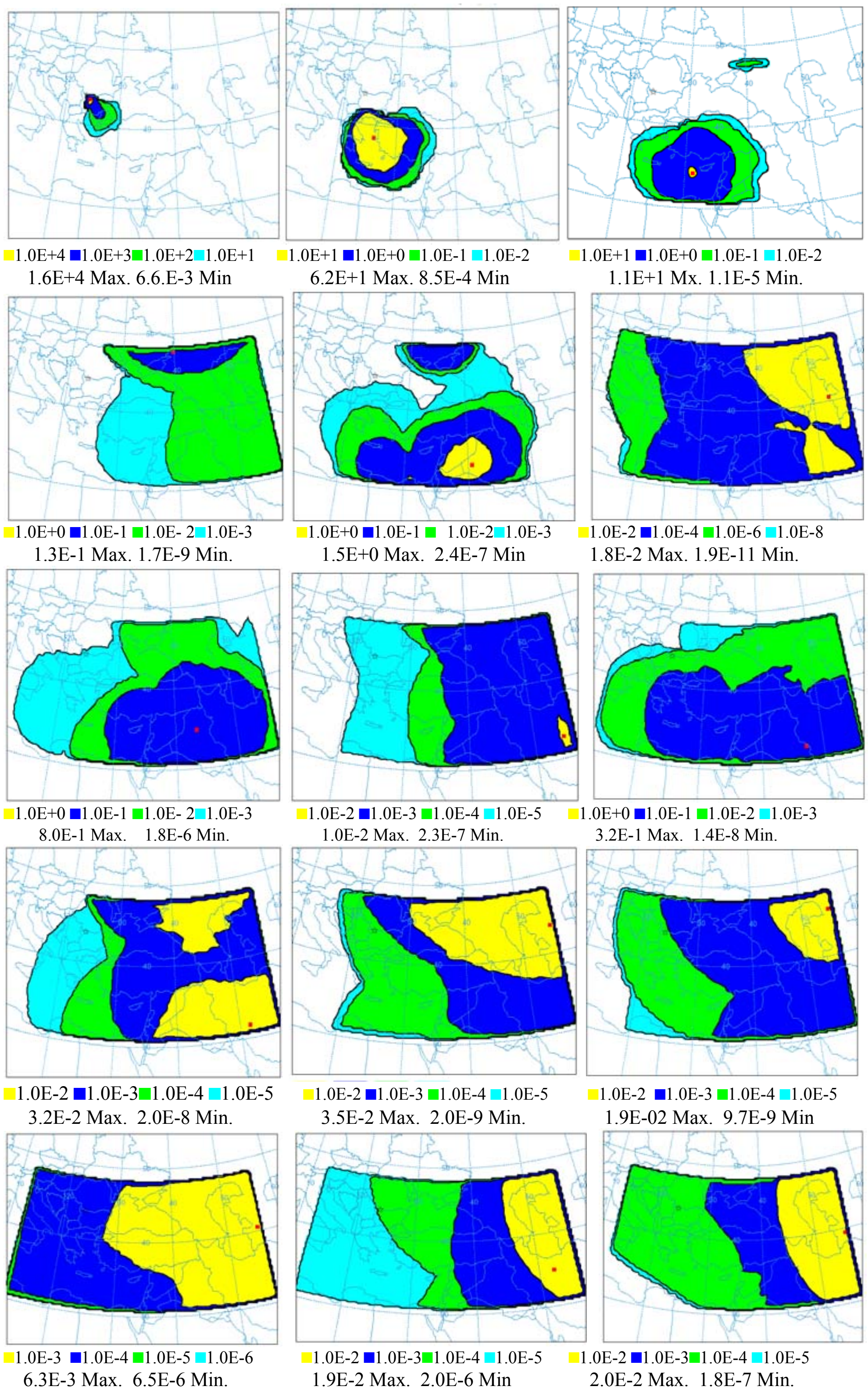


Figure 4.1 Ground Level Activities of the Cs-137 and I-131 Isotopes for the Kozloduy Accident Scenario (7-22 April 2000) (Bq/m^3)

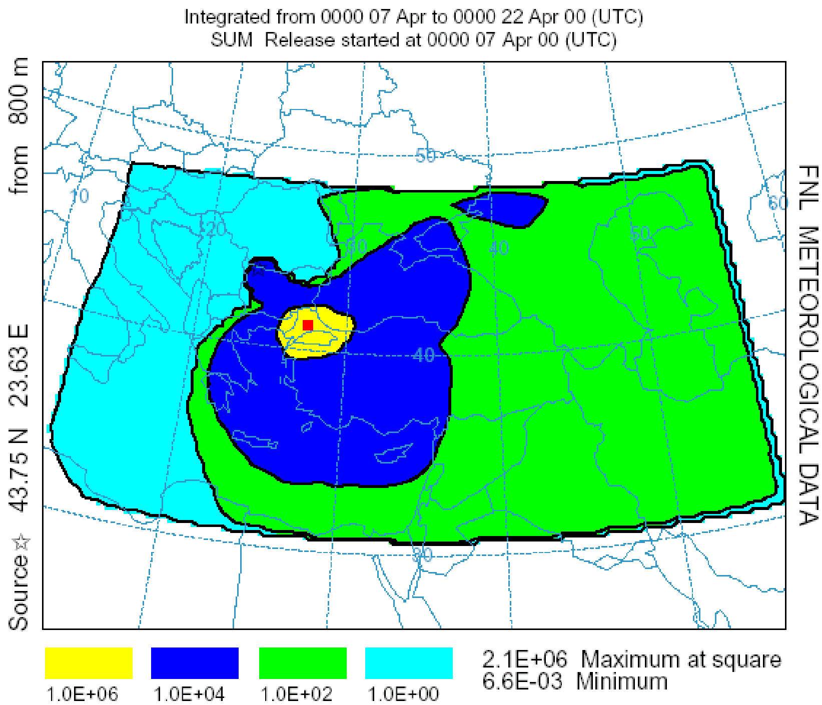


Figure 4.2 Cumulative Deposition Pattern of the Cs-137 and I-131 Isotopes for the Kozloduy Accident Scenario -Deposition (Bq/m^2) at ground level

The pattern of cumulative radioactivity deposition in 15 days is depicted in Figure 4.2. Within 15 days after the accident radioactive cloud affected fairly large area exceeding Italy on the west and east coast of Caspian Sea in the east. In most of this area deposited activity ranged between 1 and 100 Bq m^{-2}, but in area including most of the western Turkey deposited activity levels are as high as 10 000 Bq m^{-2} and in a small area including Trakya and Marmara regions of Turkey deposited activity levels are in the order of 10^6 Bq m^{-2}. Interestingly, the area with the highest deposition values does not include the grid where Kozloduy NPP is located. This is due to movement of the plume from that site within the first day after accident, consequently deposition values observed at the location of the accident is due to deposition in the first day. However, radioactive cloud resulting from accident moved back and forth over Turkey and resulted in larger deposition of radioactivity.

Ground level activities and deposition pattern described above should be explained with the prevailing meteorology in the region during accident. Thirteen-day-long and 72 hours-long forward trajectories starting at the accident site and at the time of accident are depicted in Figure 4.3. The vertical profiles of the trajectories at all levels are given in Figure 4.4.

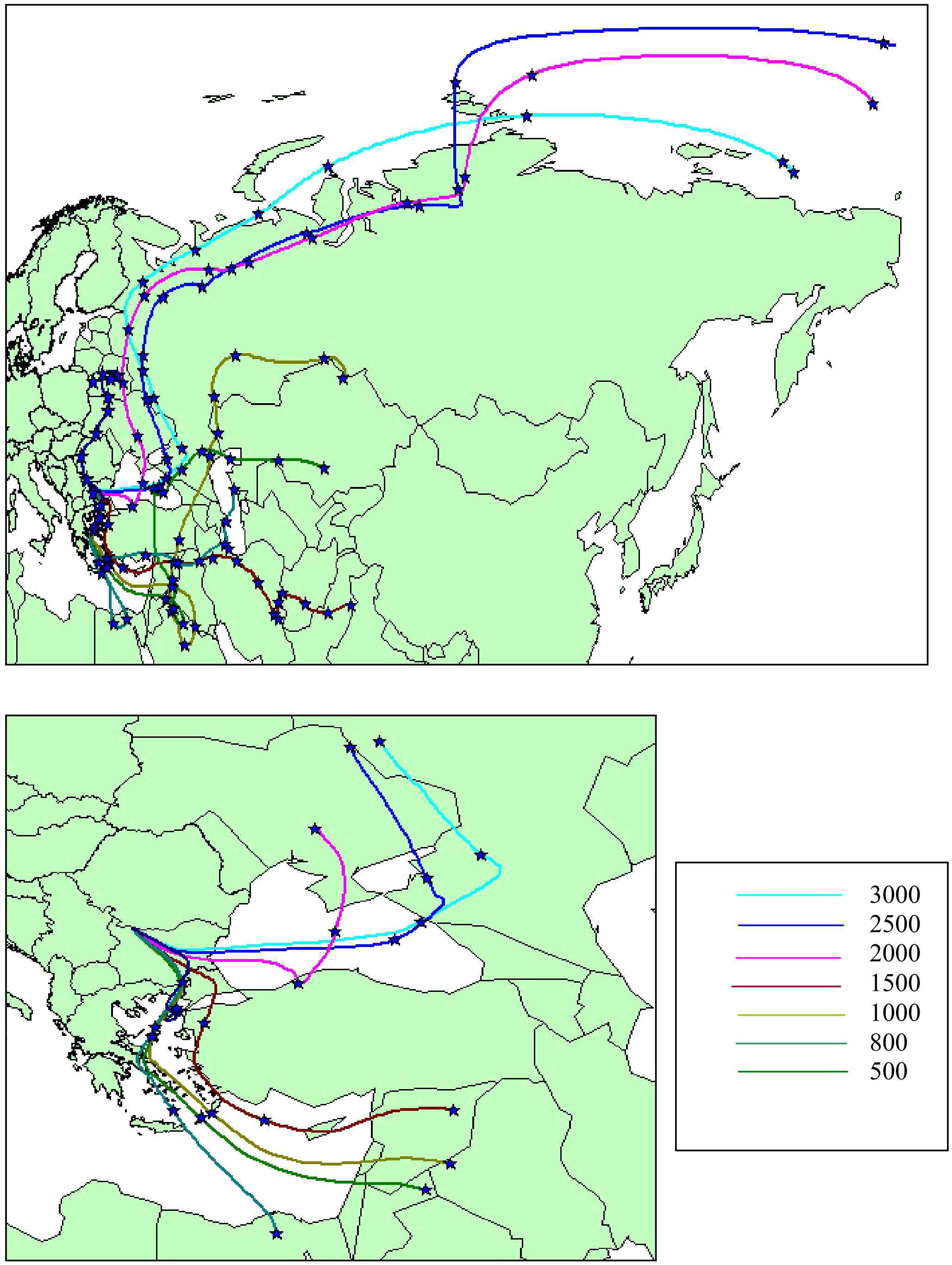


Figure 4.3. 314 and 72 hr-long forward trajectories starting at 500 m, 1000 m, 1500 m, 2000 m, 2500 m and 3000 m at the time of Kozloduy accident

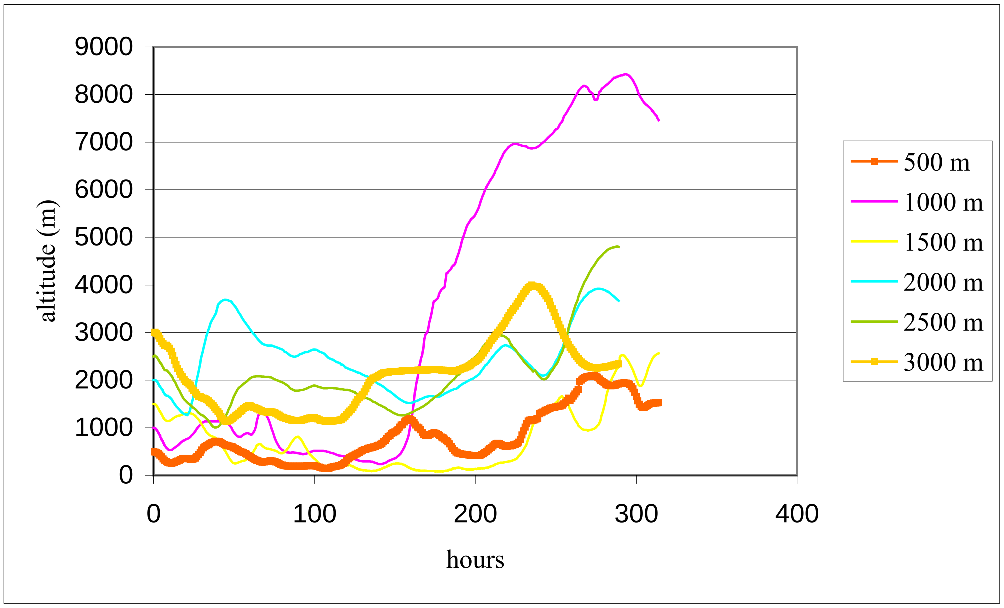


Figure 4.4. Vertical profiles of trajectories corresponding to Kozloduy accident

In this study emissions are assumed to occur at 800 m altitude (the reason for selecting 800 m altitude as emission point will be discussed in the next section). But this does not mean that the radioactive plume will follow 800 m trajectory in all 15 days. Radioactive plume after it is released to the atmosphere is picked up by the winds (trajectory) at that altitude and will be transported along the trajectory. As long as the plume is intact it will follow the path of the 800 m trajectory. But in time the plume gets dispersed and broadens. As it gets broad in x, y and z directions some portions of it will be picked up by air masses that are following trajectories at different altitudes. Consequently while main plume follows a certain trajectory radioactive material picked up by an air mass at a lower or higher altitude can move it to a totally different direction. This is how areas impacted by the radioactive cloud become wider in time and this is why radioactive material is deposited in areas that are not on the path of the trajectories. It may be safe to assume that in the first day the plume is rather intact and follows the path of the 800 m trajectory. However starting with the second day direct relation between the trajectory path and location of radioactivity may not exist.

It should be noted that, although plume disperses and diffuses with the mechanism described above, the main part of the radioactivity will still be associated with 800 m air mass. In order to relate observed deposition pattern and ground level activities with meteorology, air mass movements at various atmospheric levels, rather than only 800 m altitude must be investigated. For this reason, forward trajectories shown in Figures 4.3 and 4.4 are calculated for starting points at 500 m, 800 m, 1000 m, 1500 m, 2000 m, 2500 m and 3000 m altitudes.

There are few points worth noting in Figures 4.3 and 4.4. As can be seen in figure 4.3, there are significant differences in the paths of the trajectories at below and above 1500 m. Trajectories with starting point higher than 1500 m move very fast and leave the region within one day. By the end of 13-day period these trajectories arrive to almost to the eastern cost of Asia. Furthermore, in the first day after the accident they spent most of their time over the Black Sea and have very little contact with Turkey.

Trajectories with starting point lower than 1500 m, on the other hand, show a distinctly different pattern. These trajectories remain in the region for 4 – 7 days, stayed at very low altitude <500 m during that period. Based on this argument it can be concluded that the movement of radioactive plume from Kozloduy accident resulting in ground level activities and deposition pattern is determined primarily by the movement of air masses below 1500 m.

Very high ground level activities and cumulative deposition observed in the Marmara region is, because trajectories at all three levels (500 m, 1000 m and 1500 m) reached the Marmara region within 24 hours as can be seen in Figure 4.3.

The movement of the plume toward Mediterranean Sea in the second and third days after the accident agrees with the trajectory paths in all there levels, which travels along the Aegean Sea toward Mediterranean Sea. Sudden movement of radioactive cloud to north in the 4^{th} and 5^{th} days after the accident agrees nicely with the northward movement of 1000 m trajectory.

It can be concluded that, the development of the plume (ground level concentrations) and observed deposition pattern after the Kozloduy accident can be explained with atmospheric transport process within first 1500 m of the atmosphere.

The same runs were also performed for a potential accident in the proposed Akkuyu nuclear power plant. The accident that occurred in February 21, 2000 resulted in the highest deposition of radioactivity over Turkey. This was the case for both isotopes and for their sum.

The distribution patterns for radioactivity during 15 days after the nuclear accident are depicted in Figure 4. 5. Within 24 hours after the accident, the radioactive plume reaches to the northern coast of the black sea. As one would expect, the highest activity levels in the atmosphere is observed at the site of accident. It should be noted that, although activity generated in the proposed Akkuyu NPP is almost twice higher than the activity generated in the Kozloduy NPP, the ground level concentrations in the case of the proposed accident at Akkuyu are nearly an order of magnitude smaller than that of the proposed accident at Kozloduy for the most active parts. This can be only explained by the difference of the weather pattern, which causes the highest deposition following the proposed accident at both reactors. The most radioactive part of the plume, where atmospheric activity levels are in the order of 1000 Bq m^{-3}, is located over a narrow strip covering the region approximately between Kayseri and Ankara.

It should also be noted that most of the Eastern Black Sea coast of Turkey is under the influence of radioactive plume in the first day. As pointed out previously location of the radioactive plume after the first few days of accident is very important, because these are the days when atmospheric activity levels are the highest and most of the activity is deposited ground, both of which have significant impact on the health effects of the accident, particularly on early effects.

At the second day, activity level in the plume decreased by three orders of magnitude (at the most radioactive part) and ranges between 1 and 0.001 Bq m^{-3}. The most active part of the plume is located on the northeastern coast of the Black Sea. Most of the eastern Turkey are under the influence of 0.01 – 0.001 Bq m^{-3} activity levels. Only the eastern Black Sea coast are influenced by the most active part of the radioactive plume. In the third day, the plume moves on and disperses toward northeast the most active part of the plume is located on the 45N latitude. The activity levels in the plume ranges between 1 and $1x10^{-6}$ Bq m^{-3} and the activity over Turkey is in the 10^{-2} – 10^{-4} Bq m^{-3} range. In this day the part of the plume over Turkey is dispersed toward west and in this way most of the country, except Trakya, Marmara and a small part of the western Black Sea regions is influenced by the radioactive cloud.

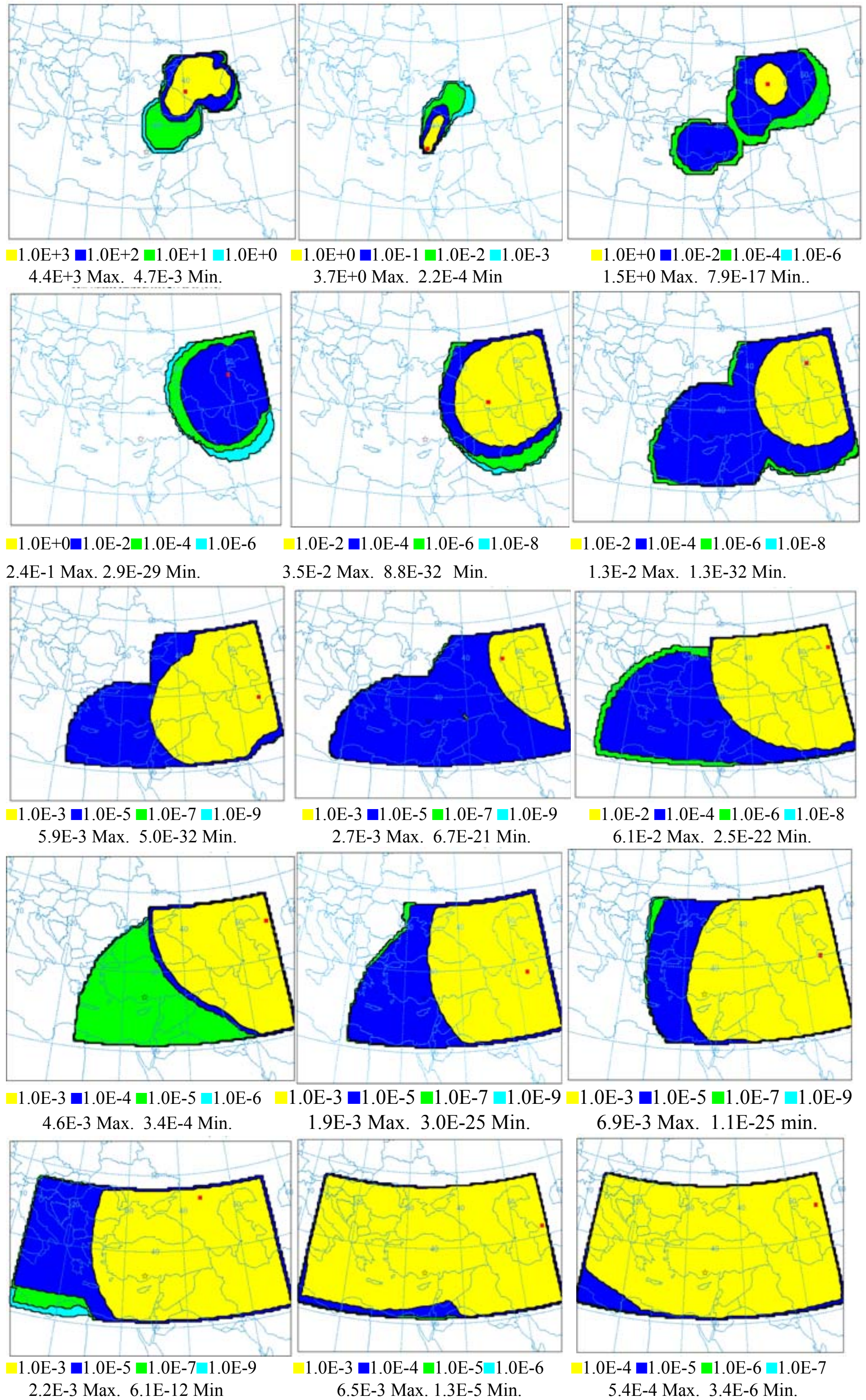


Figure 4.5. Ground Level Activities of the Cs-137 and I-131 Isotopes for the Akkuyu Accident Scenario (21- February 2000) (Bq/m^3)

Movement of the cloud to Northeast and west at the same time is due to different wind directions in different parts of the atmosphere.

In the third and fourth days, westerly winds in the upper atmosphere moves the radioactive cloud to east and in those days the plume is located over Caspian Sea and Iran. Only eastern part of Turkey are under the influence of radioactivity in these days and levels affecting this part of the country varies between 10^{-2} – 10^{-4} Bq m^{-3}.

In the following three days the plume is dispersed and carried to west and the whole region bordered by Greece on the west, 45 N latitude on the north, 30 N latitude on the south and 55 E longitude on the east are influenced by the radioactive cloud. The levels of atmospheric radioactivity affecting most parts of Turkey in these days varied between 10^{-3} – 10^{-4} Bq m^{-3}. In the remaining days the plume oscillated back and fourth in the same region.

The cumulative deposition of radioactivity after the accident in proposed Akkuyu NPP is depicted in Figure 4.6. Oscillation of radioactive cloud back and forth in the region resulted in deposition of radioactivity in the whole region between Italy and East of Caspian Sea. However, the highest deposition is observed over Eastern Turkey. In this region deposition values varied between 10^{6} – 10^{2} Bq m^{-2}, which is significantly higher than 1 Bq m^{-2} deposited to the remaining parts of the region. It should be noted that the deposition pattern given in the Figure is very similar to the ground level activity pattern for the first day after the accident which clearly demonstrate that very high deposition values over the narrow strip in the Eastern Turkey is due to location of the plume in this region during first day after the accident.

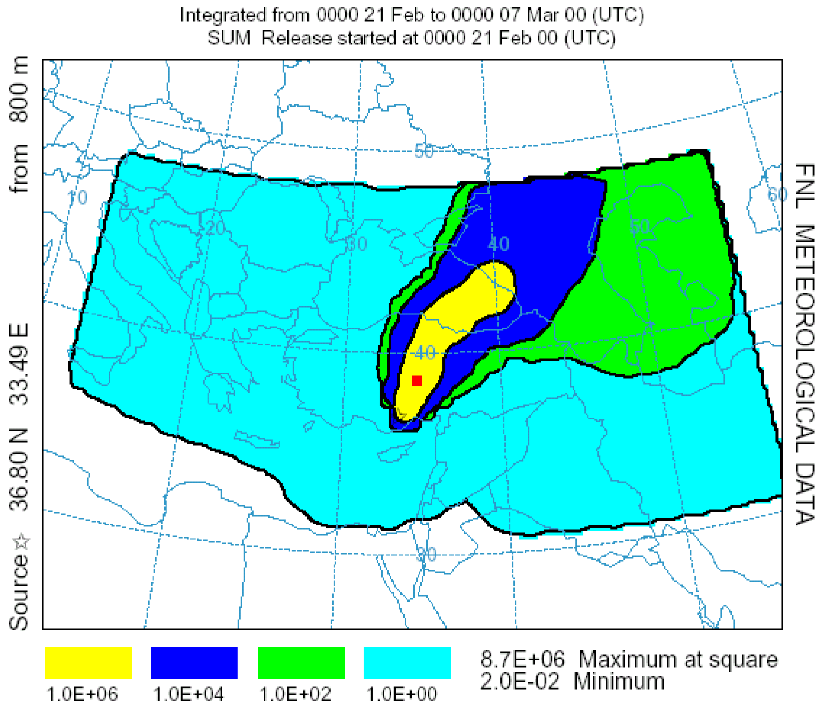


Figure 4.6. Cumulative Deposition Pattern of the Cs-137 and I-131 Isotopes for the Akkuyu Accident Scenario

Deposition (Bq/m^2) at ground level

Thirteen day long isentropic forward trajectories starting at 500 m, 1000 m, 1500 m, 2000 m and 3000 m, starting at the time and location of accident are calculated and shown in Figure 4.7.

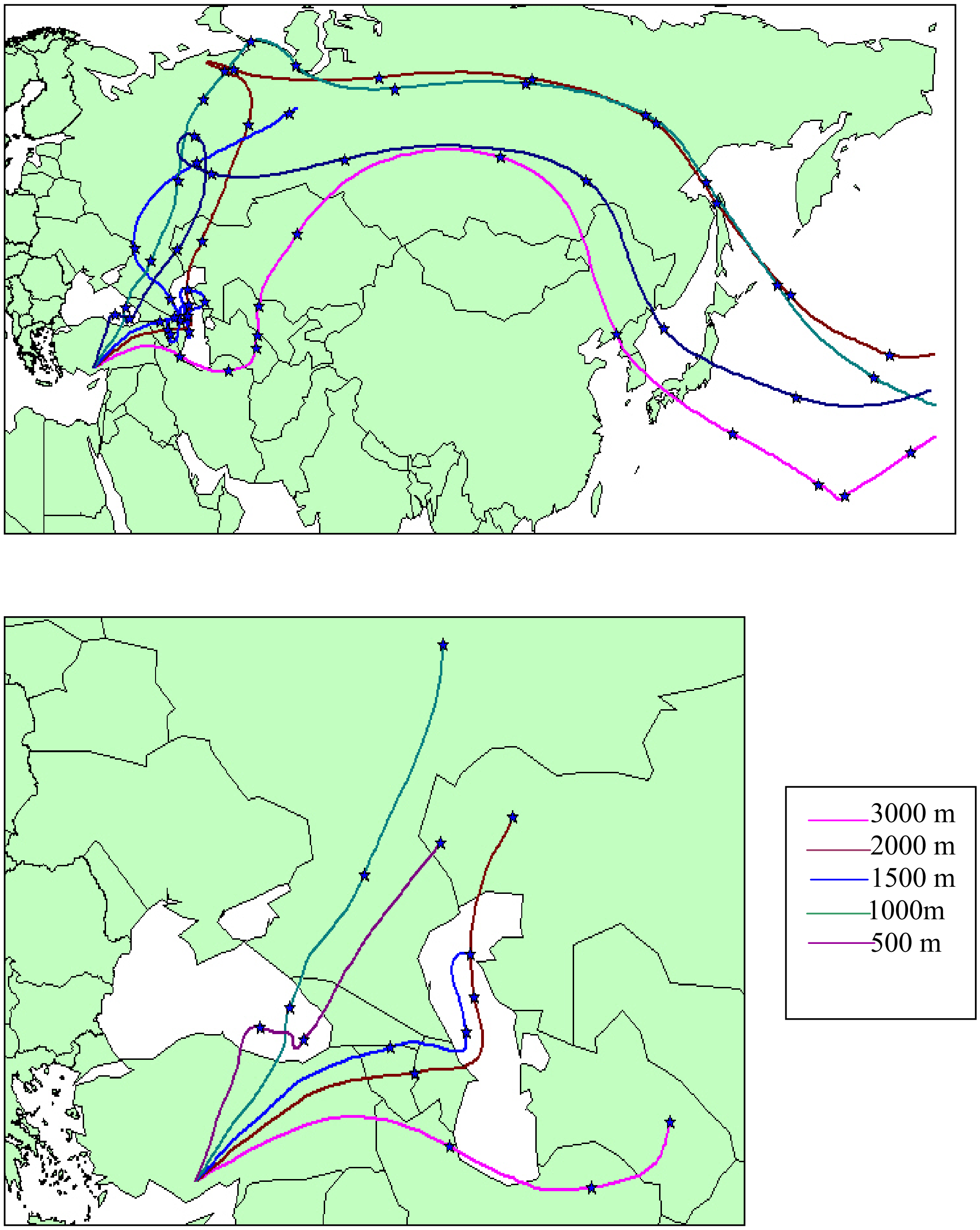


Figure 4.7. 314 and 72 hr long forward trajectories starting at 500 m, 1000 m, 1500 m, 2000 m and 3000 m at the time of Akkuyu accident.

Unlike in the Kozloduy case, trajectories at all altitudes left the study area very fast and in different directions. Trajectories starting higher than 1500 m traveled to east, crossing Southeastern Turkey in the first day, and ended up in the middle of the Pacific Ocean at the end of 15 days calculation period. Trajectories that start at 500 m, 1000 m and 1500 m, on the other hand crosses Turkey, and moves toward north.

Since the deposition to the Southeastern Turkey, which is crossed by high level trajectories within 24 hr after the accident, is very low and development of ground level activities and resulting deposition pattern clearly demonstrate a northerly movement of radioactivity, it can be concluded that the dispersion of radioactivity from Akkuyu accident is determined by air mass movements in the lowest 1500 m of the atmosphere, as in the case of Kozloduy accident.

This is further confirmed by the development of high ground level activity over the Caspian Sea in between second and seventh days after the accident, which is clearly related to the stagnant behavior of 1500 m trajectory over this area for several days after the first day of the accident.

A very important feature of the dispersion of radioactivity after the Akkuyu accident is that, the radioactive plume had left Turkey within 24 hours. That is why the ground level activity observed over Turkey was as high as 10^3 Bq m^{-3} in some of grid, did not exceed 10^{-2} Bq m^{-3} in any grid over Turkey in the remaining 14 days. Consequently, the impact of the Akkuyu accident over Turkey is due to very large ground level concentration and deposition occurred in the first day after the accident. This mechanism also explains why the highest cumulative deposition is observed over a narrow strip across the country, which is actually the path of the low level trajectories. Since the plume crossed the Anatolia in the first day after the accident, it was highly compact and this resulted in rapid decrease in deposition flux values as one goes to the east and west of the impact-strip.

It should be noted that the initial runs were performed to determine the "worst possible day" with two major short and long-lived isotopes. Consequently the distribution patterns for both ground level concentrations of isotopes and deposited radioactivity are valid, but values for ground level concentrations and deposition flux are only due to Cs-137 and I 131 and do not represent actual situation, as activities generated by other isotopes that would exist in the plume were not included in calculations. True activity values were calculated and will be discussed later in the manuscript.

4.3 Sensitivity Analyses with Different Source Term Parameters

In this study, most of the input parameters for the model, particularly those related to the accident scenario, were obtained from literature as pointed out in the previous chapter. Recent estimates of most of these parameters are fairly reliable, because Chernobyl accident provided an opportunity to confirm those values. Consequently, uncertainty arising from those parameters is much less in recent studies including ours. However, some of the source term parameters are accident specific, and the accident scenario developed for the Kozloduy and Akkuyu plants are not the same with the accident that occurred in Chernobyl, where steam explosion and subsequent graphite fire resulted continuous emission of radionuclides for a 10-day long period. Sensitivity runs were performed to see the effect of these input parameters on the deposition and ground level concentrations. These model runs were performed only for the Kozloduy plant.

The parameters that were selected for sensitivity runs are release height, which is important for subsequent transport of radioactivity, release duration and release rate, which determine the radioactivity level transported from source to receptor. It should be noted that calculations of both release duration and rate involves several individual parameters and assumptions. Instead of performing sensitivity runs for each parameter separately, running model for the release duration and rate was used to evaluate them collectively.

The values of release height, release duration and rate used in the sensitivity study and actual simulation for Cs-137 and I-131 are given in Table 4.1.

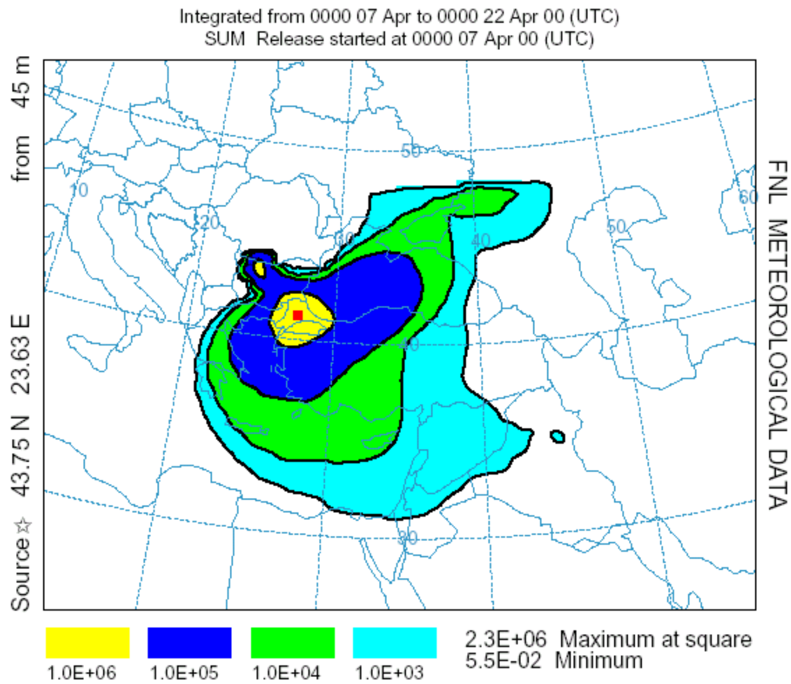
The effect of the release height was investigated by performing simulations in which the radioactivity is assumed to be emitted at two different levels, namely 45 m and 800 m into the atmosphere. Forty-five meter release height corresponds to the case where radionuclides are emitted directly from the reactor building without any force to rise them in the atmosphere. Eight hundred m release height, on the other hand, refers to the case where emission occurs with significant rigor that forces isotopes at higher levels in the atmosphere. Obviously in the catastrophic accident scenario developed for this study, 800 m plume rise seems more realistic compared to ground level emissions.

Table 4.1. The Values of Different Source Term Parameters Used in HySPLIT for Sensitivity Runs

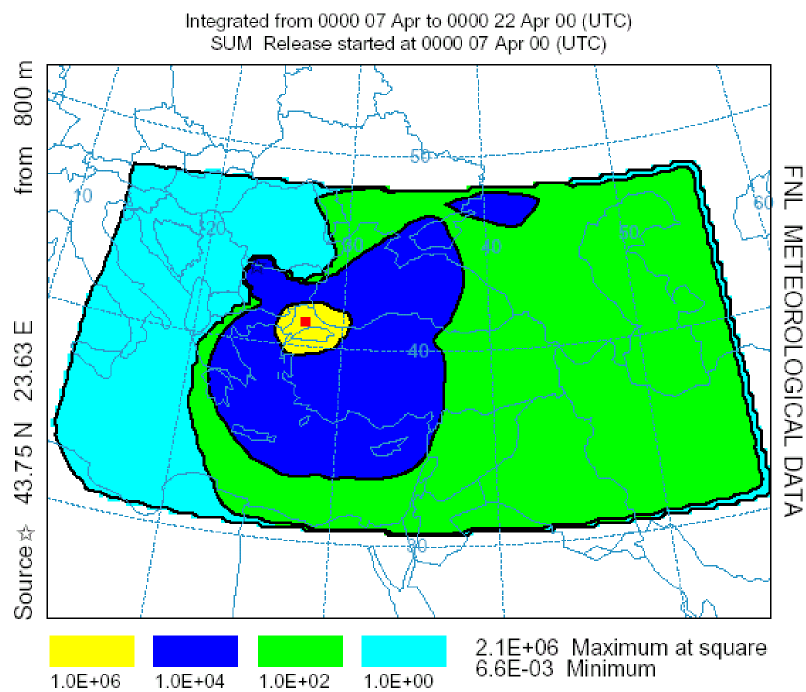
	Cs-137 release height (m) release duration (hrs) release rate (Bq/hr)	**I-131** release height (m) release duration (hrs) release rate (Bq/hr)
Sensitivity Run with release height	45 1 $0.193 x 10^{17}$	45 1 $4.70 x 10^{17}$
Sensitivity Run with release duration	800 6 $0.032 x 10^{17}$	800 6 $0.783 x 10^{17}$
Sensitivity Run with release rate	800 1 $0.231 x 10^{17}$	800 1 $0.738 x 10^{18}$
Actual parameters	800 1 $0.193 x 10^{17}$	800 1 $4.70 x 10^{17}$

Both cumulative depositions of isotopes in 15 days for the 45 m and 800 m releases are given in Figure 4.8 and development of ground level concentration patterns for the 45 m release is given in Figure 4.9. The ground level concentration pattern for the 800 m relase has been already given in Figure 4.1.

The release from 45 m results in higher deposition of radioactivity in the vicinity of the plant, but the difference between the two cases become small in the grids that are far from the source. This observation is in general agreement with Slaper (1994) who observed higher deposition values within 500 km of the source and insignificant differences at longer distances.



a)45 m Release



b) 800 m Release

Figure 4.8.Cumulative Deposition Patterns of the Cs-137 and I-131 Isotopes for the 45 m and 800 m Release Heights

Deposition (Bq/m^2) at ground level

However, the distance in which the 45 m release results in higher deposition and ground level concentrations compared to emissions to 800 m is found to be longer than 500 km in our sensitivity study. For example, emissions at 45 m produce higher deposition in The Marmara region, which is farther away than 500 km, but the difference in depositions resulting from 45 m and 800 m releases becomes insignificant at the Central Anatolia and Eastern Anatolia. On the other hand, emissions to 800 m generated a larger affected area. The region extending from Italy on the west and east coast of the Caspian Sea on the East is affected from the radioactive cloud when isotopes were emitted to 800 m altitude. It should also be noted that deposited activities were not large in most of this region.

The results obtained from development of ground level activities (isotope concentrations) were not as straightforward as the results from deposition calculations. In the first day after the release, ground level concentrations of isotopes resulting from 45 m release were higher in the close vicinity of the plant, and the difference was smaller at the grids which are not in the immediate vicinity of the power plant .

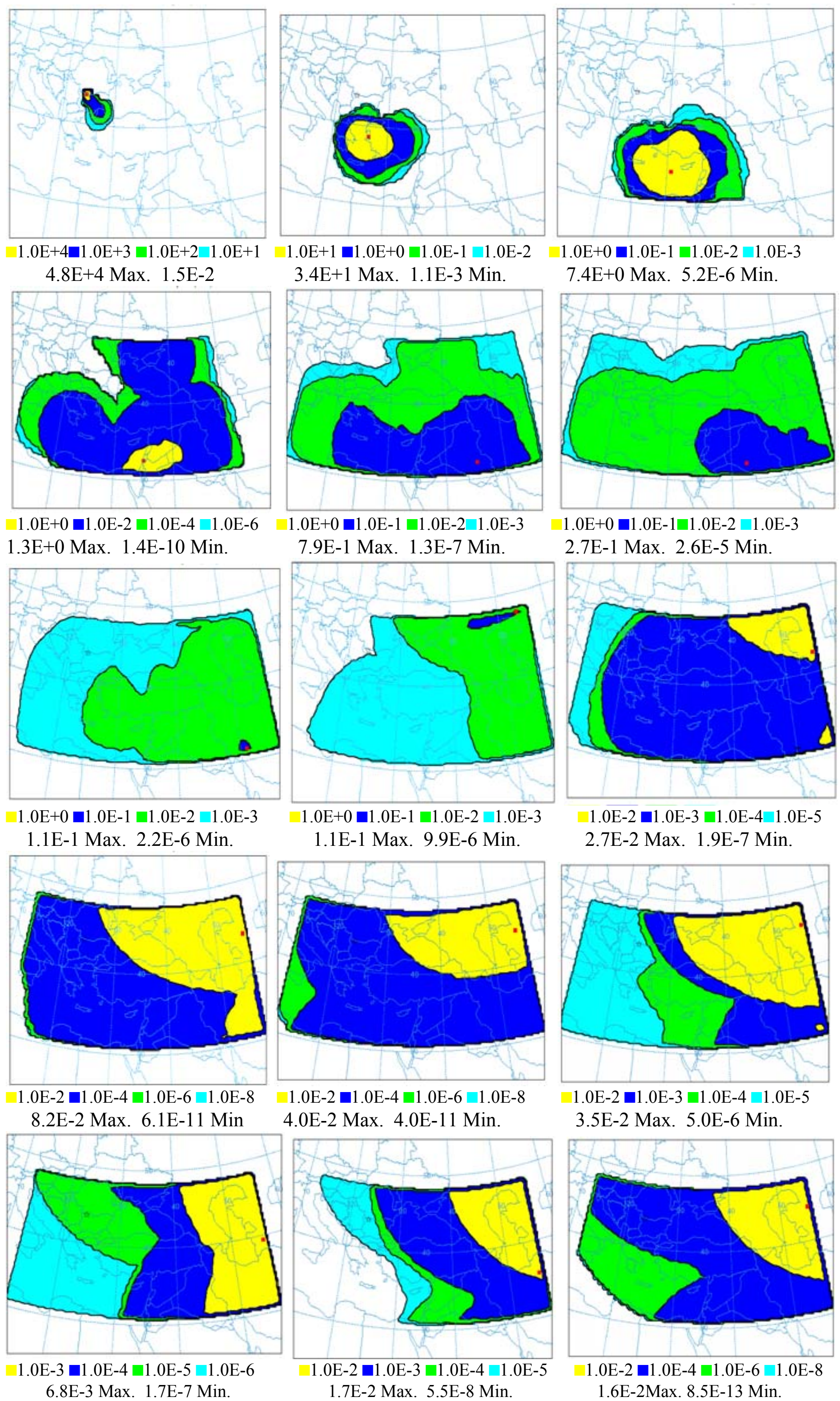


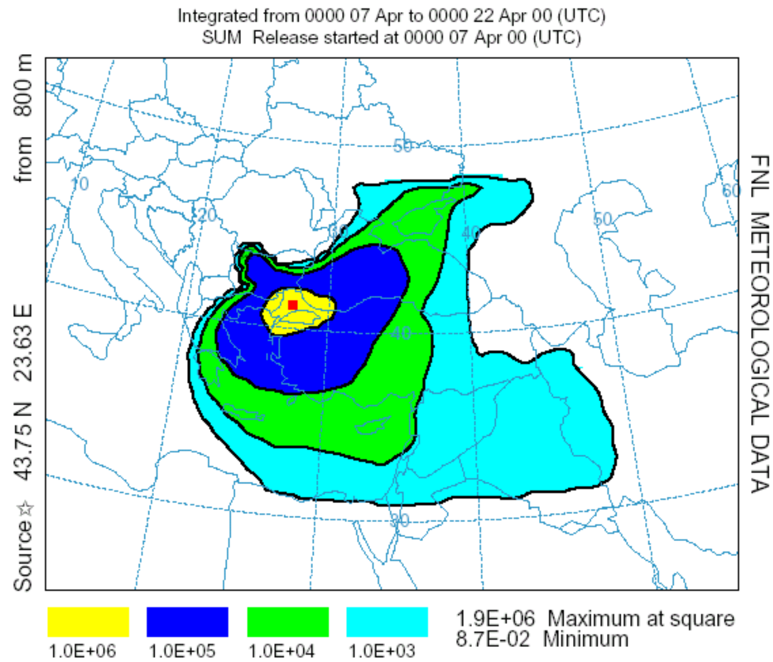
Figure 4.9. Ground Level Activities of the Cs-137 and I-131 Isotopes for the 45 m Release Height (7-22 April 2000) (Bq/m^3)

The distribution of the cloud and hence ground level activities resulting from 45 and 800 m releases were similar in the second day after the accident. However, the ground level activities observed from the two cases differed substantially in the following days and both releases generated higher ground level activities in different days. Higher ground level radionuclide concentrations were calculated for 800 m release height in days from April 8th to April 13th ,2000. Whereas, higher ground level activities were found for 45 m release for the remaining days.

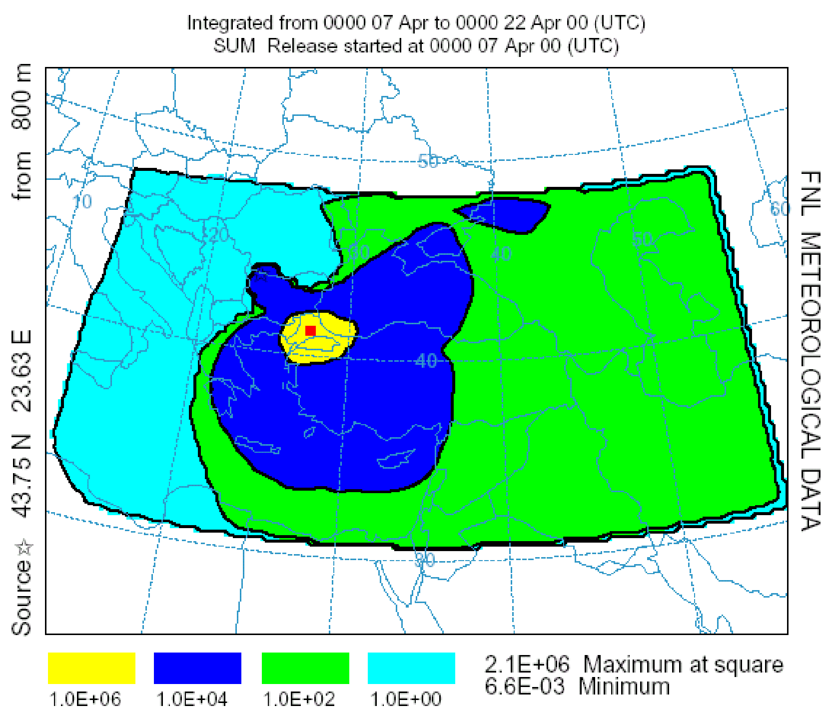
Slaper (1994) performing a similar study for nuclear power plants in Europe suggested that concentrations of isotopes are higher in the case without plume rise within about 500 km, but the difference between the two cases seems to decrease at longer distances. This generally agrees with the results obtained in this study, where we also found that concentrations of isotopes are higher in the immediate vicinity of the Kozloduy plant in the case of 45 m release. However, the distance at which 45 m release generated higher ground level concentrations is not as large as 500 km. One should not expect exact match in this sort of studies, because dispersion of radionuclides depends on air mass movements in different altitudes, which cannot be exactly the same at two different locations and at two different times.

In this study release of isotopes to 800 m was adopted as such a high altitude release generates a larger affect area and is more realistic compared to emissions at the ground level.

A second sensitivity test was performed to determine the effect of release duration. The two cases studied were one hour and six hour-long accidents (release durations). Since the ground level activity and cumulative deposition values depend also on emission rate, total amounts of isotopes released in one hour in case-1 and six hours in case-2 are assumed to be the same. This means that in 1-hour long accident scenario, all isotopes are released fiercely within one hour, whereas in the 6-hr case the same amount of radioactivity is released at a slower rate. The cumulative depositions of isotopes in the two cases investigated are depicted in Figure 4.10. The development of ground level activity in 15 day simulation for the six hour case is given in Figure 4.11. The ground level activities for the one hour case has been already given in Figure 4.1.



a)6 hr Release



b)1 hr Release

Figure 4.10 Cumulative Deposition Patterns of the Cs-137 and I-131 Isotopes for the 1-hr and 6-hr Release Duration Cases

Deposition(Bq/m^2)

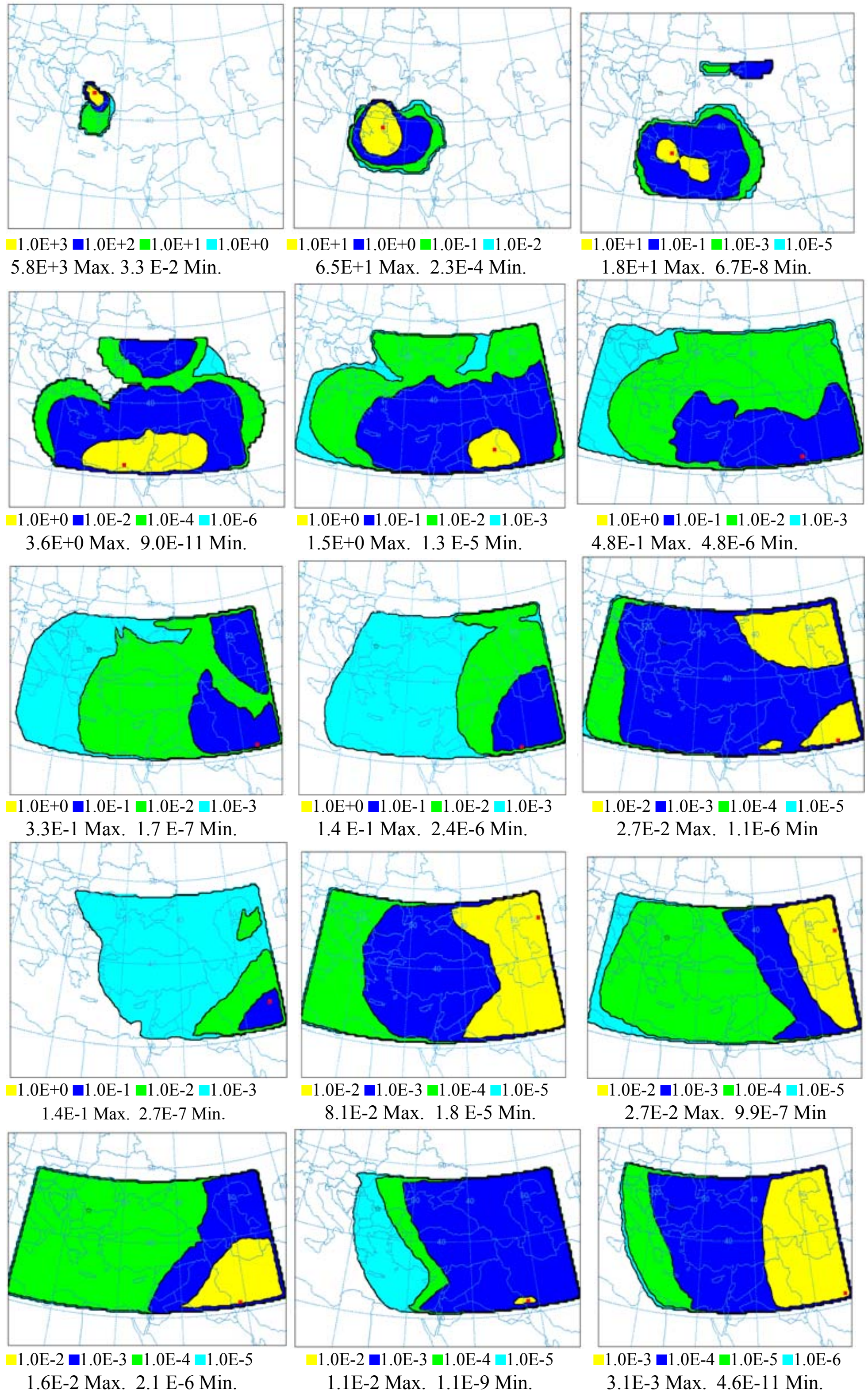


Figure 4.11. Ground Level Activities of the Cs-137 and I-131 Isotopes for the 6-hr Release Duration (7-22 April 2000) (Bq/m^3)

The region where the cumulative deposition of isotopes are the highest is the same for both cases both in terms of location and area. In this region, which is located over the Marmara region in Turkey, the deposition flux is as high as 10^6 Bq m^{-2}. However, the activity value of the region where deposition flux is smaller than 10^6 Bq m^{-2} is higher in the case of prolonged release scenario.

Like deposition, ground level activity generated by the 6-hr release scenario is higher than the ground level concentrations generated by the 1-hr release case, except for the first 24 hrs after the accident. For the first day, ground level activities produced by the 1 hr case was significantly higher.

Although the results of the sensitivity test indicated that prolonged release of radioactivity generates higher ground level activity levels and wider impact area, 1 hr release was adopted in this study, because prolonged emissions is not possible in the accident scenario adopted for this study.

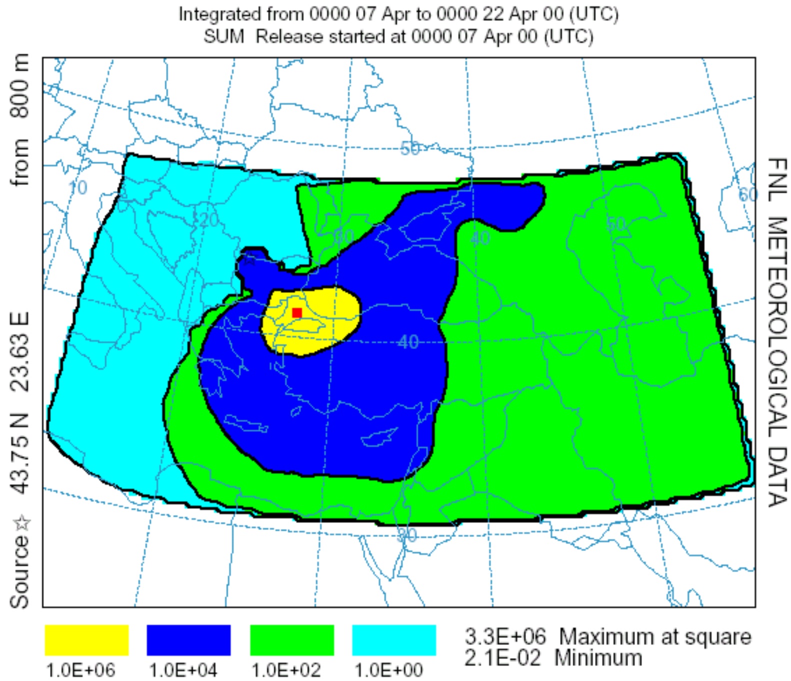
The third sensitivity test was performed to investigate the release rate of isotopes on the ground level activities and deposition fluxes. In this study, the release rate (fractions released from the core) used is 25% for Cs-137 and 35% for I-131. These values were obtained form the literature as the most likely emission rates for the type of accident used. In the sensitivity test these values are compared with the higher release rates observed in the Chernobyl accident. In the Chernobyl accident, the release rates were 30% for Cs-137 and 55% for I-131 (OECD/ NEA, 2002).

The ground level activities for the lower release rate were given in Figure 4.1. respectively. The cumulative deposition patterns for the lower and higher cases and ground level activities generated by the higher release rate are given in Figures 4. 12 and 4.13.

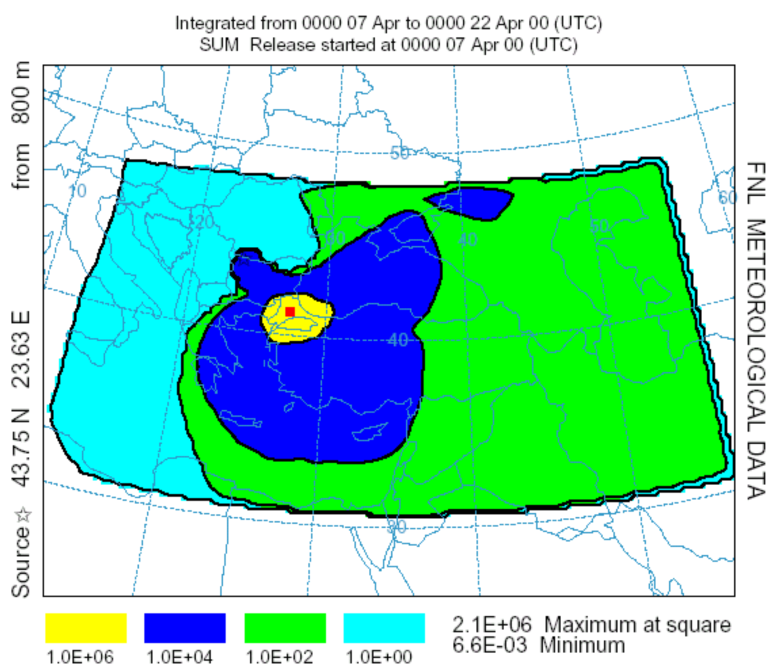
Although the Chernobyl release rates are higher than the release rate used in this study, ground level activities in Figure 4.13 are not dramatically different from the ground level activities calculated using %25 Cs-137 and 35% I-131 release rates, which are shown in Figure 4.1. Ground level activities, in addition to dispersion also depend on the scavenging of radioactive material from atmosphere by wet and dry deposition. The larger activities generated using Chernobyl fractions are probably removed at a faster rate from the atmosphere resulting in lower ground level activities with the smaller-fraction case.

Unlike ground level activities, cumulative deposition patterns obtained using high and low release rates are different. The location of the region with the highest deposition flux is the same in both cases (over the Marmara region in Turkey). However, this region is wider in the calculations with Chernobyl release rates. The regions with smaller deposition values are also wider in the high release rate case. This observation confirms our earlier suggestion that higher activities released in the accident are removed faster from the atmosphere.

Although the Chernobyl release fractions do produce higher deposition of radioactive material, these parameters were not used in this study, because Chernobyl type accident cannot occur in the Kozloduy NPP. Since in the light water reactors like Kozloduy the Chernobyl type steam explosion that was due to the graphite moderator in that type reactor cannot occur.



a)Higher Release Rate



b)Lower Release Rate (actual case)

Figure 4.12. Cumulative Deposition Pattern of the Cs-137 and I-131 Isotopes for the Higher and Lower Release Rates- Deposition (Bq/m^2) at ground level

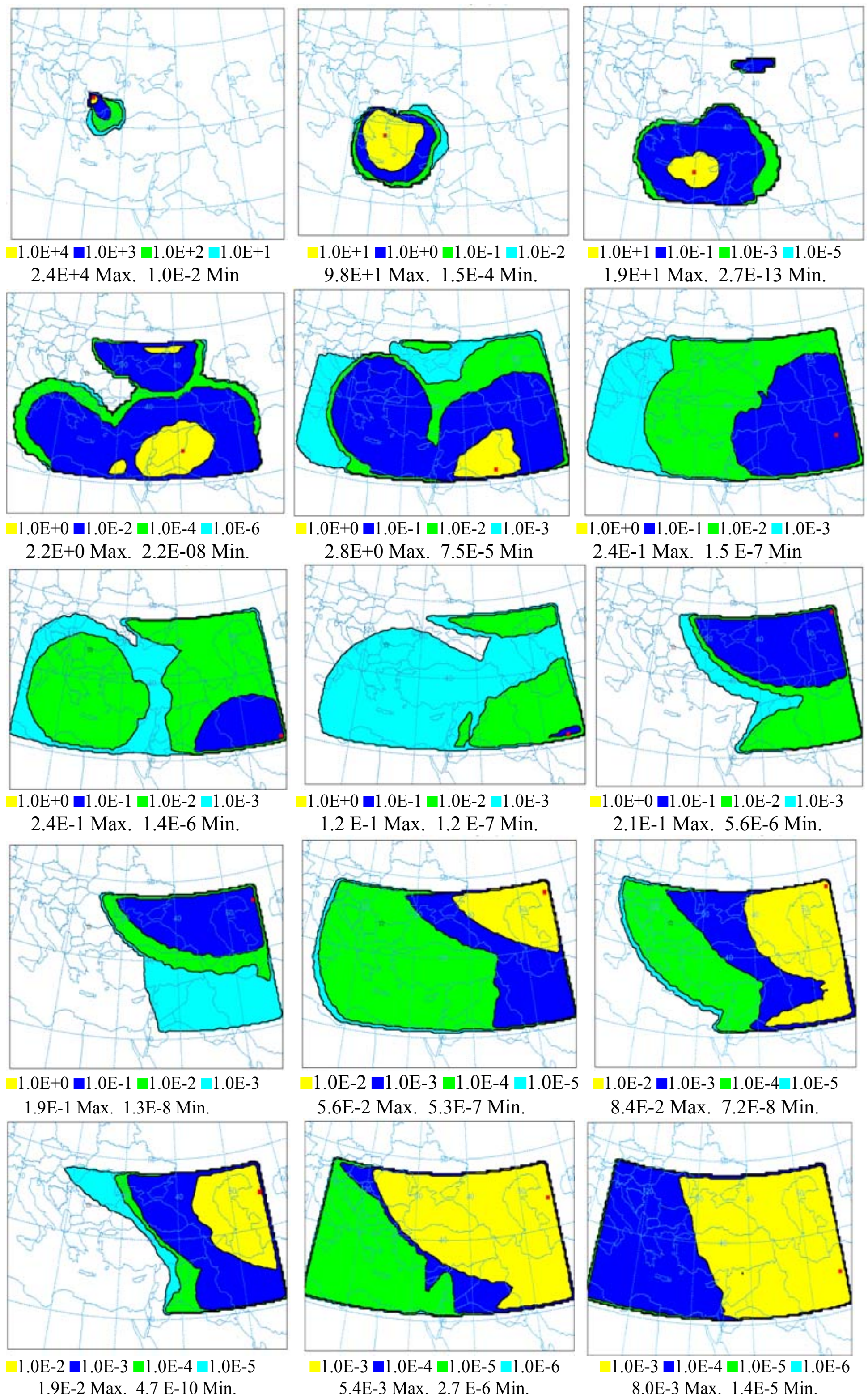


Figure 4.13 Ground Level Activities of the Cs-137 and I-131 Isotopes for the Higher Release Rate- Concentration (Bq/m^3) averaged between 0-10 m

4.4 The Results of Actual Simulation of Release

As pointed previously, initial runs for both nuclear power plants were performed to determine the meteorological conditions that would result in the highest radioactivity depositions over Turkey.

After the days that result in the highest deposition and ground level concentrations were determined in the initial runs one model run was performed for each NPP including 64 isotopes known to have health effects for the public. The isotopes included in these runs cover a wide range of separate isotopes, as well as elemental, organic and particulate iodine species.

The model input parameters for Cs-137, organic, elemental and particulate forms of I-131 and Xe-133 are listed in Table 4.2 and 4.3 for Kozloduy and Akkuyu NPPs, respectively. Input data in tables are provided only for these isotopes, because values for most of the parameters in Tables 4.2 and 4.3 are very similar for all other isotopes, the only differences being in their decay half-lives and emission strengths.

The cumulative deposition of radioactivity from 64 radioisotopes, within 15-day period after the Kozloduy accident, is depicted in Figure 4.14. Although ground level activity (Bq m^{-3}), for both Kozloduy and Akkuyu NPPs are included in risk assessment part of the study, they will not be discussed in this section, because development of radioactive plume in both cases is determined by the revealing meteorology in those days and appearance of the plume will not be any different than those discussed in initial runs.

The deposition pattern after the accident at Kozloduy NPP suggests that the Marmara, northern Aegean and western Black Sea regions of Turkey will be seriously affected. The highest deposition is observed in the Marmara region. All of Trakya and the region extending from İstanbul to Çanakkale and to Bursa receive deposition fluxes as high as 10^6 Bq m^{-2}. Deposition fluxes on the West of Ankara is 10^5 Bq m^{-2} and flux at west of Erzurum is 1000 Bq m^{-2}. Deposition flux over the rest of the country, which is actually a small area on the eastern end, is smaller than 1000 Bq m^{-2}.

Comparison of Figures 4.14 and 4.2, where deposition was calculated using only cesium and iodine, can provide information on the affect of all other isotopes on cumulative activity deposition. The two figures do not look like similar due to different legends and scaling used. The maximum deposition in both cases is 10^6 Bq m^{-2}, indicating that addition of all other isotopes did not result in higher maximum deposition of radioactivity. However, the area that suffers from 10^6 Bq m^{-2} fluxes is significantly larger when all isotopes are included in calculations. This region covers Trakya and Anatolian cost of the Marmara Sea when only cesium and iodine isotopes are used, but extends to Bursa on the East and east of Çanakkale on the South when all isotopes are included in calculations. The deposition fluxes calculated using all isotopes on other parts of Turkey is approximately an order-of-magnitude higher than deposition fluxes calculated in initial runs. For example the activity deposition in the city of Erzurum is 100 Bq m^{-2} when only cesium and iodine isotopes are sued in calculations and 1000 Bq m^{-2} when all isotopes are used.

The ground level activities, although not shown as a figure are correspondingly higher when all isotopes are included in concentration calculations.

The deposition pattern obtained after the accident at Akkuyu NPP is depicted in Figure 4. 15. The highest deposition values were observed in the strip between Niğde-Nevşehir and Kayseri and the area of maximum deposition extends all the way to the north coast of the Black Sea. Deposition fluxes in this maximum affected area are in the order of 10^7 Bqm^{-2}. Deposition fluxes on the Eastern Turkey vary between 10^5 and 10 Bq m^{-2}. The western part of Turkey, which is the most heavily populated area in the country, is not affected significantly from the accident in Akkuyu NPP. Deposition fluxes in this region are smaller than 10 Bq m^{-2}.

The comparison of the Figure 4.14 and 4.15 is important to assess relative impacts of the accidents that can occur in the two NPPs. There are number of notable differences on the deposition of radionuclides emitted, as a result of accidents, from the two NPPS. Three main differences that should be noted are in the maximum radioactivity deposited, area of impact and rates of changes in deposition flux as a function of distance from the source.

The maximum deposition flux from the Kozloduy plant is 10^6 Bq m^{-2} whereas it is 10^7 Bqm^{-2} for the accident in Akkuyu NPP, which indicates that an accident in the Akkuyu NPP is expected to deposit an order-of-magnitude higher radioactivity in limited regions in Turkey. Furthermore, the area covered by this maximum deposition is significantly larger for the Akkuyu NPP. In case of an accident in Kozloduy NPP the maximum amount of radioactivity is expected to deposit in the

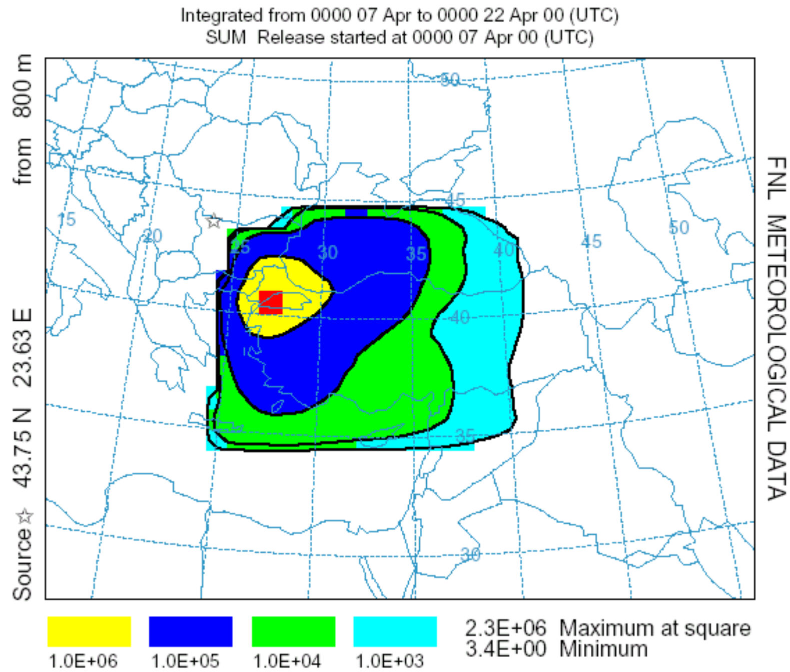


Figure 4.14. Cumulative Deposition Pattern for the 64 Isotopes for the Kozloduy Accident Scenario -Deposition (Bq/m^2) at ground level

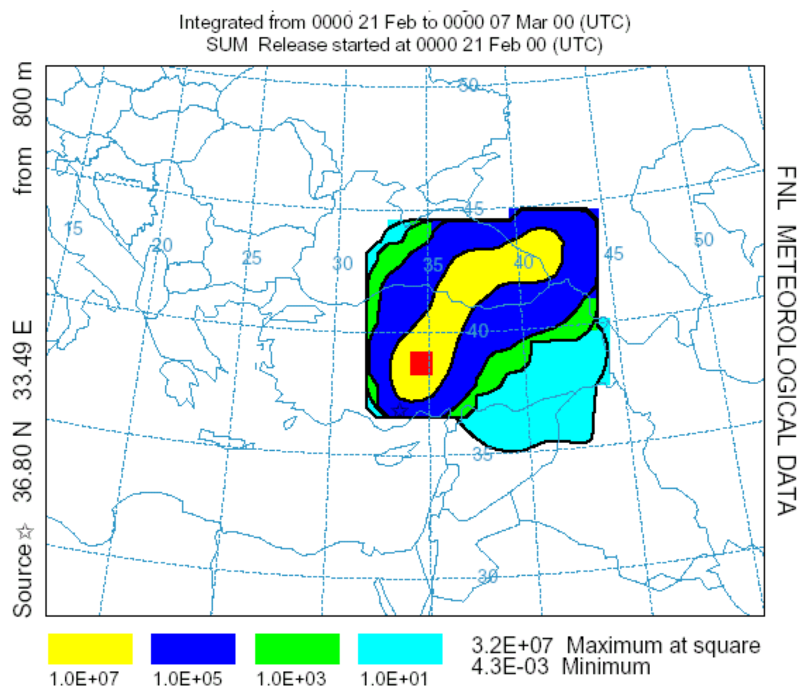


Figure 4.15. Cumulative Deposition Pattern for the 64 Isotopes for the Akkuyu Accident Scenario-Deposition (Bq/m^2) at ground level

Trakya and Marmara regions, whereas a similar accident at Akkuyu would result in 10^7 Bq m^{-2} radioactivity deposited in whole strip between Niğde Nevşehir and Kayseri. This strip crosses Turkey and extends to the north of the Black Sea. However, it should be noted that the impact of a nuclear accident depends not only on the deposition flux and ground level activities generated, but also depends on the population living in the region where deposition occurs. The impact area of the Kozloduy maximum deposition lies in the most heavily populated part of Turkey and hence an accident in Kozloduy, although generates smaller maximum deposition can have more serious health effects for the population in Turkey. This issue will be discussed more quantitatively in the subsequent sections where health risks are calculated.

In both cases the deposition flux decreases as a function of distance from the source, but the rate of decrease within Turkey is significantly smaller for the Kozloduy case. For example the deposition flux at the southeast corner of Turkey is 100 Bq m^{-2} for the Kozloduy NPP and 10 Bq m^{-2} for the Akkuyu NPP. An opposite pattern is expected, because of the shorter distance between Turkish border and Akkuyu. The observed unexpected flux values are due to location of the radioactive cloud within first few days after the accident. As pointed out in previous sections, in the Akkuyu accident, the radioactive cloud at all altitudes left the county within a day in NE wind direction. Consequently, although a large quantity of radioactivity is deposited along the path of the air mass trajectory, there was little radioactivity left in the atmosphere to be deposited in the following days. This rapid movement of air masses at all altitudes also explains why deposition flux values decrease rapidly on both sides of the radioactive plume trajectory and why fairly low flux values are observed in the south east Turkey, which is relatively close to accident site. Probably a lot more deposition has occurred on the path of the plume trajectory in the regions that lies to the NE of the Black Sea and beyond our study area.

In Kozloduy accident, the radioactive cloud is carried directly to the Marmara and Aegean regions in the first day between 500 – 1500 m altitudes and remained in the region for most of the 15 days. Since Turkey was on the path of the plume trajectory and not perpendicular to trajectory as in the case of Akkuyu accident, radioactivity from Kozloduy accident affected most of the country whereas plume from the Akkuyu accident strongly affected a limited region.

Table 4.2. The Values of HySPLIT Input Data for the Actual Simulation Modeling the Accident at Kozloduy

	Cs-137	I-131particulate	I-131elemental	I-131organic	Xe-133
Start. time (y m d h)	00 04 07 00 00	00 04 07 00 00	00 04 07 00 00	00 04 07 00 00	00 04 07 00 00
Starting location (lat., lon., agl)	43.75 N 23.63 E 800	43.75 N 23.63 E 800	43.75 N 23.63 E 800	43.75 N 23.63 E 800	43.75 N 23.63 E 800
Total run time (hrs)	360	360	360	360	360
Direction	forward	forward	forward	forward	forward
Top of model (m)	5000	5000	5000	5000	5000
Vertical	Isentropic	Isentropic	Isentropic	Isentropic	Isentropic
Set up met. files	Fnl.apr00.001-002	Fnl.apr00.001-002	Fnl.apr00.001-002	Fnl.apr00.001-002	Fnl.apr00.001-002
Emission rate (Bq/hr)	0.193E+17	0.447E+18	0.228E+17	0.705E+15	0.245E+19
Hrs of emission (hrs)	1	1	1	1	1
Release start (y m d h min)	00 04 07 00 00	00 04 07 00 00	00 04 07 00 00	00 04 07 00 00	00 04 07 00 00
Center (lat. lon.)	39 N 33 E	39 N 33 E	39 N 33 E	39 N 33 E	39 N 33 E
Spacing (lat. lon.)	1 1	1 1	1 1	1 1	1 1
Span (lat. lon.)	8 16	8 16	8 16	8 16	8 16
Number of vertical levels	2	2	2	2	2
Height of the levels (m)	0 10	0 10	0 10	0 10	0 10
Interval (hrs)	00 24 00	00 24 00	00 24 00	00 24 00	00 24 00
Particle diam., density, shape	1 1 1	1 1 1	0 0 0	0 0 0	0 0 0
Velocity (m/s), MWt (g), A-ratio, D-ratio, Henry	0.002 0 0 0 0	0.002 0 0 0 0	0.02 0 0 0 0	0.0002 0 0 0 0	0 0 0 0
Henry's(M/a),	0	1	3.24	0.19	0
In-cloud (l/l),	3.2E+05	3.2E+05	3.2E+05	3.2E+05	0
below-cloud (1/s)	5.0E-05	5.0E-05	5.0E-05	5.0E-05	0
Rad.half life (days)	10976	8.065	8.065	8.065	0.19E +13
Resuspension factor (1/m)	1E-06	1E-06	1E-06	1E-06	0

Table 4.3. The Values of HySPLIT Input Data for the Actual Simulation Modeling the Accident at Akkuyu

	Cs-137	I-131Particulate	I-131elemental	I-131organic	Xe-133
Start. time (y m d h)	00 02 21 00 00	00 02 21 00 00	00 02 21 00 00	00 02 21 00 00	00 02 21 00 00
Start. location (lat, lon,m agl)	43.75 N 23.63 E 800	43.75 N 23.63 E 800	43.75 N 23.63 E 800	43.75 N 23.63 E 800	43.75 N 23.63 E 800
Total run time (hrs)	360	360	360	360	360
Direction	forward	forward	forward	forward	forward
Top of model (m)	5000	5000	5000	5000	5000
Vertical	Isentropic	Isentropic	Isentropic	Isentropic	Isentropic
Set up met. files	Fnl.feb00.002 -mar00.001	Fnl.feb00.002 -mar00.001	Fnl.feb00.002 -mar00.001	Fnl.feb00.002 -mar00.001	Fnl.feb00.002 -mar00.001
Emission rate (Bq/hr)	0.4375E+17	0.1014E+19	0.5177E+17	0.1601E+16	0.5567E+19
Hrs of emission (hrs)	1	1	1	1	1
Release start (y m d h min)	00 02 21 00 00	00 02 21 00 00	00 02 21 00 00	00 02 21 00 00	00 02 21 00 00
Center (lat. lon.)	39 N 33 E	39 N 33 E	39 N 33 E	39 N 33 E	39 N 33 E
Spacing (lat. lon.)	1 1	1 1	1 1	1 1	1 1
Span (lat. lon.)	8 16	8 16	8 16	8 16	8 16
Number of vertical levels	2	2	2	2	2
Height of the levels (m)	0 10	0 10	0 10	0 10	0 10
Interval (hrs)	00 24 00	00 24 00	00 24 00	00 24 00	00 24 00
Particle diameter, density, shape	1 1 1	1 1 1	0 0 0	0 0 0	0 0 0
Velocity (m/s), mol.wght (g), A-ratio, D-ratio, Henry	0.002 0 0 0 0	0.002 0 0 0 0	0.02 0 0 0 0	0.0002 0 0 0 0	0 0 0 0 0
Henry's(M/a), In-cloud (l/l), below-cloud (1/s)	0 3.2E+05 5.0E-05	0 3.2E+05 5.0E-05	3.24 3.2E+05 5.0E-05	0.19 3.2E+05 5.0E-05	0 0 0
Rad.half life (days)	10976	8.065	8.065	8.065	0.19E +13
Resuspension factor (1/m)	1E-06	1E-06	1E-06	1E-06	0

4.5 Radiation Dose Received at Receptors

The first step in assessment of the risk caused by both reactor accidents is to determine the total dose acquired by the population living in a region. The methodology used in dose calculations was presented in section 3.6. Dose was first calculated for each of the three exposure pathways and then the total dose acquired is calculated as the sum of the doses from individual pathways.

The dose and subsequent health-risk calculations were performed for 12 cities in Turkey. The criteria in selecting these receptor areas were the population and location within the country. The cities selected as receptor points for risk calculations include Ankara (4 007 860) , Konya (2 217 969), Samsun (1 203 681), Kocaeli (1 203 335), Balıkesir (1 076 347), Erzurum (942340), İstanbul (10 033 478), İzmir (3 387 908), Manisa (1 260169), Adana (1 854 270), Antalya (1,726,205), Şanlıurfa (1 436 956). The numbers in parenthesis in this list are the populations of the cities in the year 2000 (SSI, 2000). The total population of these 12 cities is 30 350 518 which make up 45% of Turkish population. In addition to these 12 receptors, dose and health risk calculations were also performed in the grids with the highest deposition for each of the NPPs.

For both accident scenarios the accumulated lifetime dose commitment at receptors are given in Table 4.4.

For most of the cities located at the western parts of Turkey, such as, İstanbul, İzmir, Kocaeli, Manisa and Balıkesir the dose acquired from Kozloduy NPP is 6 to 7 orders-of-magnitude higher than the dose acquired from a potential accident in Akkuyu NPP.

Table 4.4 Accumulated Lifetime Dose Commitment Received at Receptors Following the Proposed Accidents From Kozloduy and Akkuyu Plants

Receptors	Accumulated Lifetime Dose Commitment (Sievert)	
	The accident at Kozloduy	The accident at Akkuyu
Ankara	$8{,}90\times10^{-3}$	$1{,}90\times10^{-7}$
Konya	$3{,}00\times10^{-3}$	$6{,}10\times10^{-7}$
Samsun	$1{,}10\times10^{-4}$	$6{,}70\times10^{-2}$
Kocaeli	$5{,}00\times10^{-3}$	$4{,}50\times10^{-9}$
Balıkesir	$1{,}10\times10^{-2}$	$4{,}80\times10^{-9}$
Istanbul	$1{,}30\times10^{-2}$	$1{,}50\times10^{-9}$
Izmir	$3{,}60\times10^{-3}$	$5{,}50\times10^{-9}$
Manisa	$4{,}20\times10^{-3}$	$6{,}50\times10^{-9}$
Adana	$2{,}90\times10^{-4}$	$5{,}40\times10^{-7}$
Antalya	$1{,}70\times10^{-3}$	$9{,}70\times10^{-8}$
Erzurum	$1{,}90\times10^{-5}$	$2{,}10\times10^{-5}$
Şanlıurfa	$5{,}70\times10^{-5}$	$2{,}70\times10^{-6}$
The grit with maximum deposition	$2{,}40\times10^{-2}$	$1{,}10\times10^{-1}$

The difference in cities at the central Anatolia, such as Ankara and Konya is not as large, but still the dose value obtained due to Kozloduy accident is almost three orders of magnitude higher than the dose acquired due to Akkuyu accident. The dose obtained due to Kozloduy accident is higher even in Şanlıurfa which is located on the South Eastern part of Turkey, meaning, very far from Kozloduy site and relatively close to Akkuyu.

The only two cities where dose obtained due to Akkuyu is higher than or comparable to the dose obtained due to Kozloduy accident are Samsun and Erzurum. In Samsun, the dose due to Akkuyu is two orders of magnitude higher than the dose due to Kozloduy. In Erzurum, the doses due to both accidents are very close to each other.

The dose due to Akkuyu accident in the grid that corresponds to maximum deposition is approximately a factor of 10 higher than the dose in the corresponding grid for the Kozloduy accident. This is due to higher deposition flux at the maximum-deposition grid in the case of Akkuyu accident, as discussed in the previous section.

The foregoing discussion clearly demonstrates the dominating effect of the Kozloduy NPP on deposition of radioactivity over Turkey and doses acquired by Turkish population. This is rather unexpected, because the amount of radioactivity emitted to the atmosphere from Akkuyu accident, which depends on core inventory and proportional to the power rating of the reactor, is approximately a factor of two higher than the radioactivity emitted in Kozloduy accident. Furthermore, one would expect higher doses due to Akkuyu NPP simply because the location of the accident is closer to all of the receptors selected in this study. The observed higher impact of Kozloduy accident is entirely due to prevailing meteorological conditions at the time of the accidents in both NPPs. The trajectory analysis for the transport of radioactive plumes from Kozloduy and Akkuyu NPPs were discussed in the previous section and earlier in the manuscript. Briefly, the plume generated by the Akkuyu accident had originally higher burden of radionuclides due to its higher power rating. However, the radioactive material emitted by the Akkuyu NPP was picked up by the upper atmospheric winds and crossed the Turkey toward north and left the country within a day. Most parts of the country were outside the radioactive plume as Turkey was oriented perpendicular to the plume trajectory.

However, in the case of Kozloduy accident Turkey was along the plume trajectory and the air masses, with which the radioactivity is associated, remained in the region for a much longer time period. These two meteorological settings resulted in higher doses due to Kozloduy accident in almost all parts of Turkey, except a narrow strip that lies on the Akkuyu plume trajectory. The higher dose due to Akkuyu accident at Samsun and comparable doses found in Erzurum are because these cities are on the or close to plume trajectory from Akkuyu accident.

4.6 Health Risk Posed by the Accidents

Only the stochastic health effects of radiation have been investigated in this study; the reasons for the exclusion of the early effects will be explained in subsequent sections.

4.6.1 Individual Health Risk

The individual health risk, which includes fatal and non-fatal cancers and hereditary effects for a person due to each NPP accidents were calculated, for each of the receptor city, using the methodology given in section 3.7. The results are given in Table 4.5 for both Kozloduy and Akkuyu cases.

The individual risks for people are expected to follow similar patterns with the dose acquired, which was discussed in the previous section. The results in the table shows that in The Marmara Region where the impact of the Kozloduy NPP is the highest people will experience fatal cancer risks ranging $7x10^{-2}$ % for İstanbul and $3x10^{-2}$ %

for Kocaeli. These numbers mean that in every 10 000 people 3 to 7 are expected to die from cancer related to radiation exposure. The non-fatal cancer and hereditary risks for the same region are expected to be 0 – 1 and 0 – 2 person per 10 000 population, respectively.

Central Anatolia (Ankara and Konya) and Aegean (İzmir and Manisa) regions are expected to have slightly lower risks in all three categories. In the central Anatolia fatal, non-fatal and hereditary risks range between approximatley 2 – 5, 0 – 1 and 0 – 1 person per 10 000 population respectively. Similar risk values were also calculated for the cities in the Aegean region. Fatal and non-fatal cancer risks and hereditary risks calculated for the cities in the Mediterranean region, Black Sea region and Eastern parts of the country are approximately an order-of-magnitude smaller than the risks calculated for the cities in the Aegean coast and Central Anatolia.

The calculations for the Akkuyu accident indicated that individual risks for fatal and non fatal cancer incidences and hereditary effects are significantly smaller at all parts of Turkey, except for Samsun and to a certain extend Erzurum. For Samsun, fatal cancer risks related to Akkuyu accident is expected to be 34 person per 10 000 population. The risks of non-fatal cancer and hereditary effects are approximately 7 and 9 person per 10 000 population, respectively. As pointed out in the previous section, Samsun is located on the trajectory of the radioactive cloud from the Akkuyu accident and among 12 cities selected as receptors in this study. It is the only one located in the highest deposition area in the Akkuyu accident deposition pattern discussed earlier in the manuscript. In the narrow strip of very high deposition all three modes of health risk can be comparable or even higher than the risk calculated for the city of Samsun. For example in the grid on which the maximum amount of radioactivity was deposited including Nevşehir, Niğde and Kayseri fatal, non-fatal and hereditary effect risks are 54, 10 and 14 person per 10 000 population respectively.

Table 4.5 Individual Health Risk Posed by the Accidents at Kozloduy and Akkuyu at Receptors

Receptors	Individual health risk (%)					
	the accident at Kozloduy			the accident at Akkuyu		
	fatal	non-fatal	hereditary	fatal	non-fatal	hereditary
Ankara	$4,5x10^{-2}$	$9x10^{-3}$	$1,2x10^{-2}$	$9,5x10^{-7}$	$1,9x10^{-7}$	$2,5x10^{-7}$
Konya	$1,5x10^{-2}$	$3x10^{-3}$	$3,9x10^{-3}$	$3,2x10^{-6}$	$6,1x10^{-7}$	$8x10^{-7}$
Samsun	$5,3x10^{-4}$	$1,1x10^{-6}$	$1,4x10^{-6}$	$3,4x10^{-1}$	$6,7x10^{-2}$	$8,7x10^{-2}$
Kocaeli	$2,5x10^{-2}$	$5x10^{-3}$	$6,5x10^{-3}$	$2,3x10^{-8}$	$4,5x10^{-9}$	$5,9x10^{-9}$
Balıkesir	$5,4x10^{-2}$	$1x10^{-2}$	$1,4x10^{-02}$	$2,4x10^{-8}$	$4,8x10^{-9}$	$6,3x10^{-9}$
İstanbul	$6,7x10^{-2}$	$1,5x10^{-2}$	$1,7x10^{-2}$	$7,7x10^{-9}$	$1,5x10^{-9}$	$2x10^{-9}$
İzmir	$1,8x10^{-2}$	$3,6x10^{-3}$	$4,6x10^{-3}$	$2,8x10^{-8}$	$5,5x10^{-9}$	$7,2x10^{-9}$
Manisa	$2,1x10^{-2}$	$4,2x10^{-3}$	$5,5x10^{-3}$	$3,4x10^{-8}$	$6,5x10^{-9}$	$8,4x10^{-9}$
Adana	$1,5x10^{-3}$	$3x10^{-4}$	$3,8x10^{-4}$	$2,7x10^{-6}$	$5,4x10^{-7}$	$7x10^{-7}$
Antalya	$8,4x10^{-3}$	$1,7x10^{-3}$	$2,2x10^{-3}$	$4,8x10^{-7}$	$9,7x10^{-8}$	$1,3x10^{-7}$
Erzurum	$9,4x10^{-5}$	$1,8x10^{-5}$	$2,3x10^{-5}$	$1,1x10^{-4}$	$2,1x10^{-5}$	$2,7x10-^{5}$
Şanlıurfa	$2,9x10^{-4}$	$5,7x10^{-5}$	$7,4x10^{-7}$	$1,3x10^{-5}$	$2,7x10^{-6}$	$3,5x10^{-6}$
The grit with max. deposition	$1,21x10^{-1}$	$2,4x10^{-2}$	$3,1x10^{-2}$	$5,4x10^{-1}$	$1,1x10^{-1}$	$1,4x10^{-1}$

4.6.2 Collective Health Risk

As pointed out in earlier sections, the impact of an accident on the population as a whole depends not only on the deposition, atmospheric activity levels and dose obtained, but also on the population living in that particular area. For example the deposition, atmospheric activity levels, dose obtained and individual health risk, due to Kozloduy NPP accident, are very high over the Sea of Marmara, but these high values does not mean anything since there is no one living there. Consequently, better representation of the risk of an accident, nuclear and non- nuclear, can be obtained by multiplying the individual health risk by the number of people living in the receptor. This parameter is called “collective health risk”.The collective health risk, due to both accidents, is separately calculated for each of the 12 cities and results are presented in Table 4.6, along with the population living at the receptors. The highest impact of a potential accident at the Kozloduy NPP is expected to be seen in İstanbul, due to very large population of the city. In İstanbul approximately 7 000 people is expected to suffer from fatal cancer, 1 300 people from non-fatal cancer and 1 700 people from hereditary effects of radiation. Ankara will experience the next highest impact of radiation from Kozloduy accident, with 1,800 fatal, 350 non-fatal cancer incidents and 460 cases of hereditary effects. İzmir and Balıkesir are expected to experience similar collective health effects of Kozloduy accident. In both cities there will be 500 – 600 fatal, 120 non-fatal cancer cases and 150 – 160 people will experience from hereditary effects of radiation. Kocaeli, Konya and Manisa will experience more than 100 fatal cancer cases, more than 50 non-fatal cancer cases and more than 50 people in each of these cities will suffer from hereditary effects. The other cities will have much fewer cases of fatal and non-fatal cancer and hereditary effects.

The impact of a potential accident in the Akkuyu NPP will be very high in Samsun, but almost zero in other 11 cities. In Samsun approximately 4 100 people are expected to experience fatal cancer, 810 people are expected to experience non-fatal cancer and 1 100 people are expected to suffer from hereditary effects of the radiation from Akkuyu accident. No fatalities or sicknesses are expected in the remaining 11 cities.

It should be noted that, collective risk was not calculated for some of the cities, such as Kayseri, Nevşehir Niğde that are on Akkuyu radioactive plume trajectory. Due to very high individual health risk in this strip, collective health risks in these cities can be very high. The collective health risks from both power plants for each different geographic regions in Turkey were also calculated. However, it should be pointed that calculated collective risks for these regions are only crude approximations as they involve several additional assumptions.

Table 4.6 Collective Health Risk Posed by the Accidents at Kozloduy and Akkuyu at 12 cities

Receptors	Population	Collective health risk (number of people)					
		the accident at Kozloduy			the accident at Akkuyu		
		fatal	non-fatal	hereditary	fatal	non-fatal	hereditary
Ankara	4 007 860	1 800	360	470	0	0	0
Konya	2 192 166	330	65	85	0	0	0
Samsun	1 209 137	6	1	2	4 100	810	1 100
Kocaeli	1 206 085	300	60	80	0	0	0
Balıkesir	1 076 347	580	110	150	0	0	0
İstanbul	10 018 735	6 700	1 300	1 700	0	0	0
İzmir	3 370 866	600	120	160	0	0	0
Manisa	1 260 169	270	50	70	0	0	0
Adana	1 849 478	30	5	7	0	0	0
Antalya	1 719 751	145	30	40	0	0	0
Erzurum	937 389	1	0	0	0	0	0
Şanlıurfa	1 443 422	4	1	1	0	0	0

For this calculation, individual risks calculated for the cities in different regions are assumed to represent individual risk in the whole region. For example the individual risk for the Marmara Region is obtained by averaging individual risks calculated for

İstanbul and Kocaeli. This assumption will probably not cause significant error in the Marmara Region which is small, or in Eastern Anatolia and Southeastern Anatolia for Kozloduy accident as they are far and individual risks are already fairly small. However, the uncertainties in the Kozloduy case can be high for the Aegean and Central Anatolia regions, because individual risks in these regions decrease substantially with the distance and representing the whole region with one or two cities (İzmir and Manisa in the Aegean Region and Ankara and Konya in the Central Anatolia Region) can be a significant source of uncertainty.

The same assumption in case of Akkuyu accident would produce unacceptably high errors for the Central Anatolia and Black Sea regions, because as discussed previously, a narrow strip in the Central Anatolia region is very heavily affected from the accident in the Akkuyu NPP. However, individual risks calculated for the city of Ankara were very low as it is outside this strip and deposition flux decrease very rapidly with distance from the strip due fast transport of radioactive cloud across the Anatolia. The use of low individual risk calculated for Ankara would severely underestimate collective risk in whole Central Anatolia region. To avoid this Central Anatolia region is divided into two parts as heavily impacted area, which includes Karaman, Aksaray, Nevşehir, Kayseri, Kırşehir, Niğde, Sivas, Yozgat and Tokat, and remainder part of the region. The population living in the impacted area is 4 700 000 and population living in the other parts of the Central Anatolia region is

6 900 000 (SSO, 2000). The individual risk calculated for the city of Samsun was used to calculate the collective risk in the impacted Central Anatolia region and the individual risk calculated for the city of Ankara was used to calculate the collective risk in the remainder of the region. The collective risk for the whole Central Anatolia region was then obtained by summing the collective risks in both parts.

Similar assumptions were also applied to the Black Sea region. Small part of the Black Sea, including the coastal strip between Sinop and Samsun is affected from the passage of the radioactive cloud from Akkuyu. Very high individual risks were calculated for the city of Samsun as it is within this impact area. Consequently, individual risk calculated for Samsun cannot be used to calculate collective risk in the whole Black Sea region, most of which was not seriously impacted from the radioactive cloud from the Akkuyu accident. As in the case of Central Anatolia region, collective risk for Sinop and Samsun were calculated using the individual risk calculated for the city of Samsun, and collective risk for the rest of the Black Sea region was calculated using the individual risk calculated for the city of Ankara. Naturally, the individual risk calculated for the city of Ankara is probably not exactly the same with the individual risk in the western Black Sea region. However, in the case of Akkuyu accident, the individual risks outside the impact area are so small that an order of magnitude error in the individual risk used to calculate collective risk in the western Black Sea region would not make a substantial difference on the collective risk, because the collective risk in the Black Sea region is due to the cities of Sinop and Samsun with very small contribution by the rest of the region. The collective risks calculated for the each geographic regions in Turkey are given in

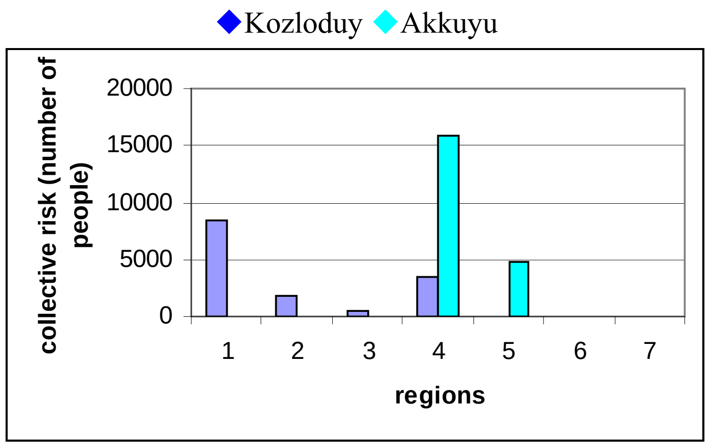
Table 4.7. The data is also presented in Figure 4.16 for easy comparison between the collective risks of Kozloduy and Akkuyu accidents.

The data in the table and figure demonstrate that all three late effects resulting from Kozloduy accident (fatal, non-fatal cancer and hereditary effects of radiation) will be dominating in the Marmara, Aegean and Central Anatolia regions. A total of 20 600 people in all regions will be affected in case of an accident in the Kozloduy NPP.

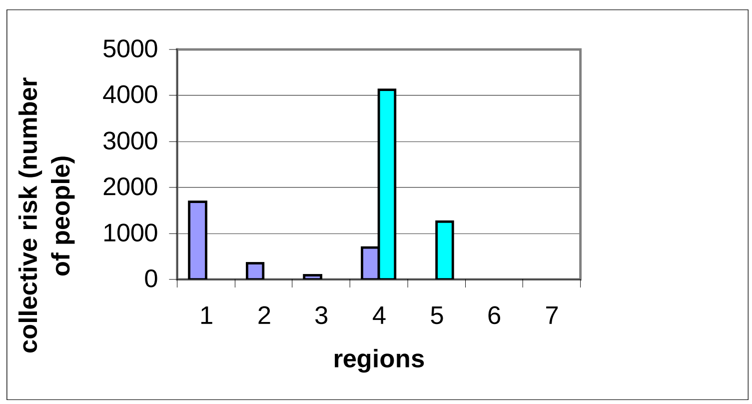
The impact of the accident at the Akkuyu NPP will be higher in the Central Anatolia and Black Sea regions affecting some 30 500 people. It should be noted that this many people will be affected due to passage of radioactive cloud in one day only.

Table 4.7. Collective Risk due to Potential Accidents in Kozloduy and Akkuyu NPPs in Different Parts of Turkey

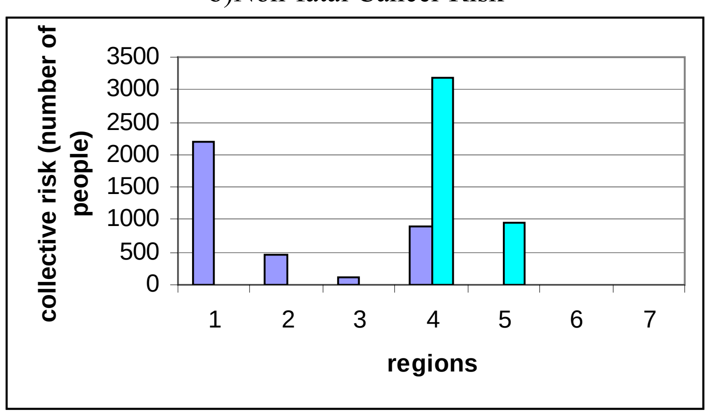
	Kozloduy			Akkuyu		
Regions	Fatal Cancer	Non-fatal cancer	Hereditary Effects	Fatal Cancer	Non-fatal cancer	Hereditary Effects
1.Marmara	8 400	1 700	2 200	0	0	0
2.Aegean	1 700	350	450	0	0	0
3.Mediterranean	450	90	110	0	0	0
4.Central Anatolia	3 500	700	900	16 000	3 200	4 100
5.Black Sea	40	0	0	4 800	1 000	1300
6.Eastern Anatolia	10	1	1	10	1	2
7.Soutern East Anatolia	20	5	0	1	0	0
Turkey Total	**14 120**	**2 846**	**3 661**	**20 811**	**4 201**	**5 402**



a)Fatal Cancer Risk



b)Non-fatal Cancer Risk



c)Hereditary Effects

Figure 4.16. Collective Risks Calculated for the Kozloduy and Akkuyu Accidents at Different Regions in Turkey

A potential accident in Kozloduy NPP will generate the largest impact on the Marmara and Aegean regions of Turkey. In these two regions a total of 17 000 people will be affected. The impact of a Kozloduy accident will also be significant in the Central Anatolia where approximately 5 000 people will suffer from fatal, non-fatal and hreditary effects of radiation.

A potential accident in the Akkuyu NPP will affect only the Black Sea and Central Anatolia regions of Turkey. However, the impact of the accident on these regions will be devastating affecting approximately 30 500 people.

The total impacts of Kozloduy and Akkuyu accidents on whole Turkey will be comparable, affecting 20,600 and 30,500 people, respectively. However, as pointed out in the above discussion people that will be affected from Kozloduy and Akkuyu accidents will not be in the same regions.

4.7. Likelihood of an Accident and Likelihood of Transport of Radioactive Cloud to Turkey in the Two Nuclear Reactors Investigated in This Study

In this study the impacts of potential accidents in the Kozloduy and Akkuyu NPPs were estimated based on the number of people that will be affected if such accidents occur and impacts turned out to be comparable in the country scale. However, the impact of a nuclear power plant also depends on probability of such accident to occur and also to the probability of occurrence of meteorological conditions that will generate the estimated risks for Turkey.

Estimation of these probabilities is beyond the scope of this study; however qualitative speculations are possible. First of all, Kozloduy is much older plant and designed with minimum safety measures. That is why it is one of the most dangerous nuclear reactors in the world. On the other hand, proposed reactor in the Akkuyu will be designed with best available safety measures. Consequently, likelihood of an accident is significantly higher in Kozloduy NPP.

Meteorology in the region had been studied by various researchers (Katsoulis and Whelpdale, 1993, Dayan and Miller, 1989, Güllü et al., 1998, Kubilay and Saydam, 1995, WMO, 1985, GESAMP, 1990). The common conclusion in all of these studies is that, the dominant flow in the region is from W, NW and N wind sectors. In approximately 70% of the time air masses affecting Turkey originate from these wind sectors. This means that transport of radioactive cloud from Kozloduy to Turkey is highly probable whenever an accident occurs. Maybe the meteorological conditions will not generate as high activity and deposition as those calculated in this study (because the worst case was selected in this study), but the plume will arrive to Turkey with approximately 70% probability.

The northwesterly upper atmospheric flow in the region transports radioactive cloud from a potential accident in the proposed Akkuyu NPP to SE in 70% of the time. The frequency of upper atmospheric flow from S, SE and SW wind sectors that can transport radioactivity form Akkuyu accident over Turkey is approximately 20% (Güllü et al., 1998). Since the worst case in this study was selected based on deposition of radioactivity over Turkey, one of these rare cases, where the upper atmospheric flow is from SE is selected. When all of these factors are considered, it can be concluded that, the likelihood of an accident and likelihood of transport of plume over Turkey if an accident occurs are higher in Kozloduy NPP.

4.8 Uncertainties

Since the work described in this manuscript is a modeling study, it includes a variety of uncertainties and the results should be viewed with these uncertainties in mind. As in any modeling study, the accuracy of the results can be better assessed and they can be put in a right perspective if the sources of uncertainties are known and appreciated.

The main sources of uncertainties in the results include uncertainties in the source term, uncertainties in the meteorological input data, uncertainties in the dose calculations, uncertainties due to risk group assumption, uncertainties in late effect calculations. These issues will be briefly discussed in the following sections.

4.8.1 Limitations of the Modeling

(i) Uncertainties in source term:

Source term is the most important parameter affecting the radiological consequences of the nuclear reactor accident. In this study release fractions of radionuclides were taken from those provided for the US light water reactors though the actual amount of the release is different even for the same type of plant depending on the specific reactor. The same accident is postulated to occur for the both reactors regardless of their different core design and operating condition. It was stated before that the unit 1 and 2 of Kozloduy plant was shutdown in December 2002 and unit 3 and 4 are planned to shutdown in 2006. It can’t be so realistic that the same accident is assumed to occur at the reactor with old and low safety level and the new reactor designed in the similar way those for the most US reactors. Also accident progression of the same accident in VVER and PWR reactors is not the same and the differences in the accident progression especially in the accident sequences and in the timing of events are caused by reactor core design (OECD/NEA, 1998).

As regard to the risk posed by the proposed reactor at Akkuyu, the construction of the PWR type reactor is open to uncertainties. The reactor can be different type like CANDU or BWR, related to the national nuclear policy and government' decision. As mentioned in previous chapters different reactor types cause different amount of release in the case of the accident. Since fission product inventory is different based on the neutron spectrum, burn up level and core inventory as described in Chapter 2.3.3.

(ii) Uncertainties due to HySPLIT and meteorological data

The dispersion code used in this study, namely HySPLIT is a well-documented and tested program, which is used widely in the literature. However, since the model simulates transport of radioactivity and other pollutants over very long distances, the topography included in the software is rather coarse. This is not a specific problem with this particular model. Most of the long-range transport models have the same deficiency. The model is shown to perform satisfactorily over reasonable topography, but can have problems, as most of the other long-range transport models, over complex terrain.

The model has an internal coordinate system of 100x100 km. Therefore meteorological changes due to the terrain effects at a shorter distance scale can't be modeled as accurately. However, shorter scale changes in transport generally occur at the lower atmosphere and have limited influence on the long-range transport, which primarily occurs in the middle layers in the troposphere.

Another source of uncertainty in the modeling arises from missing meteorological input data. The metrological input fields were obtained from NCEP's FNL archive as mentioned in Chapter 2.5.1. Some of the fields, in the form of 15 day-long files, for the year 2000 are the problematic or missing. The problematic files, which corresponded to the first 15 days of October, that of June and that of February, were replaced for corresponding periods of the year 2001 from the same data archive. Since the agreement between 2001 meteorology with long-term climatology in the region is not tested, these replacements may have caused unrealistic model results. However, it should be noted that the worst days in Kozloduy and Akkuyu do not corresponds to these periods.

4.8.2 Uncertainties due to Natural Variations

(i) Radiation dose and risk modeling:

The radiation dose received during the lifetime period and risks following the accidents were calculated manually for the selected receptor grits in this study. Since it was impractical to perform all dose calculations for each grit on Turkey some receptors carrying high population were selected. But there are many software models to calculate the dose and risk on every grit point like CAR88 PC of DOE, PC COSYMA of EC, RADRISK of EPA, and CRRIS of NEA. However these models either calculate both the atmospheric dispersion and dose or are not suitable for the usage of the result of the HySPLIT.

(ii) The risk group

In this study only the risk has been investigated only for adults representing the overall population. But the sensitivity of the people with the different ages to radiation is different. ICRP–67 (1993) specified age-dependant doses to members of the public from intake of radionuclides defining different dose coefficients for intakes for 3 months, 1 , 5, 10, 15 years and adult. The dose conversion factors are higher for children than adults and they are calculated such that; the activity in the body following intakes at these ages, continuous changes with age in the transfer rates governing the distribution and retention of the activity are obtained by linear interpolation according to age. Also the diet and behavior of the time spent indoors of the children are different than adults. Apart from the fact that doses received are higher due to higher dose conversion factors, also the risk factor is higher for children than for adults Results from BEIR V indicate a twofold higher risk per unit dose and ICRP (1991) provides estimate up to a nearly 3-fold higher risk. Slaper (1994) combined these with the higher dose received by the children and investigated that 3-4 fold higher risk for children, who are one year old at the time of the accident. In addition to the age difference, sex difference can result in different sensitivities to radiation-induced cancers due to interactions between other factors such as hormone dependent promoting factors. For radiation-induced leukaemias males are more sensitive and females are approximately three times more susceptible than males for thyroid cancer. (ICRP-60, 1990)

(iii) The complexity of late effect modeling

Hasemann (2000) stated that the calculation of the risk of suffering a late health effect as a result of an accident is complicated by a number of features. The first of them; the exposed population consists of individuals of various ages. As late effects may not appear for some tens of years after the exposure, some of the possible risk may not be expressed in the population as people may die naturally before the radiation-induced effect occurs. Most of the routes of the radiation lead to doses being delivered over a period of time. Intakes of contaminated food and external exposure from deposited activity may continue over extended periods of time, so that people who are born after the accident occurred can also be irradiated, and therefore suffer health effects, but in collective risk calculations the population numbers were obtained from the census results given for the year 2000 and the possible trends in the number of population were not taken into account. In addition the calculation of the risk of health effects allowing for time variation of dose, the age distribution of the population and the delay between exposure and the effect occurring requires the evaluation of complicated multiple integrals. Instead of this complex modeling the late effect implemented in this study is a simple approach.

(iv) Exclusion of early health effects of radiation

There are also deterministic (early) effects of radiation as stated in Chapter 2.7.4., which can be seen in the close vicinity of the plants following the nuclear accidents. Since the risk of suffering from these effects increases rapidly as the dose increases above a threshold value. These effects are calculated for the different organs for which different dose threshold values are defined, and in a different radiation dose quantity, absorbed dose, than those for stochastic effects. Different organs have different tissue weighting factors, which means the sensitivity of the organs to the radiation is different and distribution of the radioactivity within the body is also different. ICRP-60 (1999) stated that absorbed dose depend not only on the magnitude of the dose, the type and energy of the radiation (dealt with by the radiation weighting factor of photons, electrons, neutrons and protons with different energies and alpha particles etc), and the distribution of the dose within the body (dealt with the tissue weighting factor) but also distribution of the dose in time (dose rate and fraction of exposure). Since the complexity of the calculation of the absorbed dose in many organs it is necessary to use the appropriate organ dose model. But the results of the HySPLIT can't be used in any organ dose models. The combined model calculating long-range transport of radionuclides and also organ-dose for early effect, committed effective dose for late effect is necessary for this study to be cover all aspects of health risk posed by nuclear accidents. But in this study the purpose is to use HySPLIT for calculating long-range transport and then investigate the health risk using the results of this model.

4.9. The Comparison of the Risk Values Investigated in This Study and The Studies in the Literature

In this study health risks for a potential accident either within Turkey or in neighboring country on population living in Turkey were determnied by a model. The uncertainities in the results are expected to be substantial, as in any modeling study, due to numerous assumptions involved in calculations. Consequently the risks found in this study should be considered as an order-of-magnitude approximation to actual risk posed by the two NPPs included in the calculations. However, the results obtained should not be utterly wrong and so should give an idea about the impacts of the two power plants. The individual risks calculated in this study were compared with the risks calculated for other hypothetical accidents in the literature, just to show that the results are not totally out of line from the results of similar works performed elsewhere. During this comparison exercise it was quickly anticipated that such a comparison is a futile attempt, because it was impossible to find risk studies with exactly similar input parameters. It should be noted that a large number of input parameters were involved in both dispersion and risk modeling. The number of nuclear risk studies in the "**open**" literature is not very large and in existing ones, type of the reactors, type of the accident scenerios, distance scale and time scale involved in the modeling changes, which makes the comparison a difficult task. The following three studies were selected for comparison of results, because the hyphotethical accident scenerios used were reasonably close to the scenerio used in this study.

In this study the individual health risk posed by the Kozloduy NPP in Bulgaria ranges from 1210 per $1x10^6$ people in the maximum deposited grit over the Marmara Sea to 0.94 per $1x10^6$ people in Erzurum where the deposition fluxes are fairly small.

The individual risk posed by the proposed NPP in Akkuyu ranges from 5400 per $1x10^6$ people in the narrow strip including Niğde-Nevşehir-Kayseri to 0.077 per $1x10^6$ people outside the strip.

Cao et al. (1999) used the program package COSYMA to investigate the health effects and risks from accidental releases of radioactive material from the Daya Bay

NPP in Hong Kong Island. The results showed that late effects were higher in the range of 40-50 km from the reactor. The maximum collective risks reached 1,328x10^4 people out of 4 011 453 people within this region. This collective risk corresponds to 3300 people per 10^6 population. This number is in reasonable agreement with the highest individual risks found for Kozloduy (1210 per 1x10^6 people) and Akkuyu (5400 per 1x10^6 people) accidents. The highest risks found in this study were compared with the results of Cao et al. (1999), because their risks were found for the vicinity of the NPP where the accident occurred.

Slaper (1994) studied the risk posed by the NPPs in Europe in different countries based on delayed health effects of radiation. Individual health risk in Iceland, northeastern part of the Portugal and Spain was found less than 70 per 1 million population , in eastern Europe and larger parts of Russia it was higher than 70 per 1x10^6 people, in the areas where the light water graphite moderator reactors were found it was higher than 700 per 1x10^6 people, in the Netherlands it was 21 per 1x10^6 people. It is not so easy to compare the results from Slaper (1994) with ours, because (1) it is difficult to specify the distance between hyphotetical accident and target populations in Slaper (1994) study, and (2) Slapper (1994) have calculated an average risk for the whole country, whereas our results are for individual regions that are impacted from accidents. The average risk was not calculated in this study, because we do not feel that it is a correct approach as it severly underestimates the risks in certain regions, which are under the influence of radiactive cloud. But obviously the numbers reported by Slaper (1994) are within the risk ranges we found in this study.

Lo et al (2000) performed an evaluation of the emergency planning zone of nuclear power plants in Taiwan. They calculated individual late effects as a function of distance from the reactor based on a severe reactor accident asssumption. The individual risk within the reactor site was found as $7x10^{-7}$, at 2 km it was $1.4x10^{-7}$, at 4km it was $7x10^{-8}$, at 6 km it was $8x10^{-8}$, at 8 km it was $3.5x10^{-9}$. These numbers are low compared the individual risk values calculated in this study, which varies from 10^{-4} and 10^{-8} for Kozloduy and between 10^{-3} and 10^{-11} for Akkuy NPPs. It should be noted that the risk calculations that bases on dispersion modeling the region at the immediate vicinity of the NPP is the "cleanest" area, because the radioactive plume is very high in the atmosphere.

The exercise have demonstrated that comparision of results between risk studies are very difficult owing to high variability of input parameters and results generated in this study are not dramatically different from the results obtained in this study.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1.Overview

The purpose of this chapter is to conclude all the results presented in previous chapter including the highest deposition patterns, the results of dose acquired, the individual and collective risks at different parts of Turkey and to make some future recommendations in the case of such unfortunate accidents at both plants.

5.2. Conclusions

Kozloduy Nuclear Power Plant of which the shutdown of the units 3 and 4 is finally accepted by the Bulgarian government in 2006 poses considerable risk on our country. Therefore it is very important to be aware about this risk associated with that reactor. Also the Turkish government could decide to restart its nuclear energy program in which the construction of the first nuclear power plant was postponed on July 2000. So it is necessary to know about the risk posed by the proposed plant at Akkuyu, too. The purpose of this study was to investigate these subjects together with the appropriate comparison.

The results of actual simulations, part of the results presented in the previous chapter, have revealed that the highest deposition was observed in the Marmara region after a possible core meltdown accident with the catastrophic failure of the containment at Kozloduy NPP. All of the Trakya and the region extending from İstanbul to Çanakkale and to Bursa received deposition fluxes as high as 10^6 Bq m^{-2}. The highest deposition values were observed in the strip between Niğde-Nevşehir and Kayseri and the area of maximum deposition extends all the way to the north coast of the Black Sea after the same assumed accident at Akkuyu NPP. Deposition fluxes in this maximum affected area are in the order of 10^7 Bqm^{-2}. In Kozloduy accident, the radioactive cloud was carried directly to the Marmara and Aegean regions in the first day between 500 – 1500 m altitudes and remained in the region for most of the 15 days and since Turkey was on the path of the plume trajectory radioactivity affected most of the country. In Akkuyu accident, since trajectories at all altitudes crossed Turkey within a day radioactivity affected only a narrow strip leaving other parts of the country almost free of radioactive contamination.

The modeling studies have indicated that the transport of radioactive cloud during first two days after the accident is very important, because very high levels of radioactivity is deposited in the region where the cloud passed through in these two days. After the first few days activity in the cloud decrease rapidly due to both dilution of the cloud with clean air and decay of the short-lived isotopes and deposition of activity decrease proportionally.

Total dose acquired by the population living in the most populated 12 cities and the grit with maximum deposition in Turkey was calculated taking into account three pathways. The results of dose assessment for the accidents at both plants showed the dominating effect of Kozloduy. In İstanbul, İzmir, Kocaeli, Manisa and Balıkesir the dose acquired from Kozloduy NPP was 6 to 7 orders-of-magnitude higher than the dose acquired from a potential accident in Akkuyu NPP. The difference in cities at the central Anatolia, such as Ankara and Konya was not as large, but still the dose value obtained due to Kozloduy accident was approximately three orders of magnitude higher than the dose acquired due to Akkuyu accident. The dose obtained due to Kozloduy accident is higher even in the Şanlıurfa which is located on the South Eastern part of Turkey, meaning, very far from Kozloduy site and relatively close to Akkuyu. The dose acquired by population owing to a potential accident in Akkuyu NPP was significantly higher than the corresponding dose acquired from Kozloduy NPP only in the narrow strip around a hypothetical line connecting Akkuyu and Samsun. For example in Samsun, the dose due to the accident at Akkuyu was two orders of magnitude higher than the dose due to Kozloduy. Population living cities that are located within the indicated strip, such as Niğde, Kayseri, Karaman, and population received higher doses due to Akkuyu accident. The dose acquired by the population due Kozloduy accident is dominating in the remainder of the country. In Erzurum, the doses due to both accidents were very close to each other.

The individual stochastic health effects, which followed the same patterns with the dose acquired, were calculated for each cities selected as receptor in the study. The calculations for the Kozloduy NPP showed that the people would suffer from all late effects of radiation at the highest in the Marmara region. The calculations for the Akkuyu accident indicated that individual risks for fatal and non-fatal cancer incidences and hereditary effects were significantly smaller at all parts of Turkey, except for Samsun and to a certain extent Erzurum.

The results of collective health risk have shown that in the accident at Kozloduy NPP the highest impact was seen in İstanbul due not only its high activity value but also its very large population. Approximately 7 000 people was expected to suffer from fatal cancer, 1 300 people from non-fatal cancer and 1 700 people from hereditary effects of radiation in this mega city. The next highest impact was observed in Ankara, İzmir, Balıkesir, Kocaeli, Konya, Manisa and the other cities in a descending order. In the case of a potential accident at Akkuyu NPP the collective risk value was very high in Samsun but close to zero in other cities chosen as receptors. In Samsun approximately 4 100 people would suffer from fatal cancer, 810 people were expected to experience non-fatal cancer and 1,100 people were expected to suffer from hereditary effects of the radiation.

The collective risk values of all regions were also calculated assuming individual risks calculated for the cities in different regions represented individual risk in the whole region. The impact of the accident at the Kozloduy NPP was dominating in the Marmara, Aegean and Central Anatolia regions and a total of 20 600 people in all regions were affected in this case. For the accident at Akkuyu NPP the collective risk was higher in the Central Anatolia and Black Sea regions affecting some 30,500 people totally in Turkey.

Even though the probability of accidents and the transport of the radioactive cloud to Turkey in two reactors are beyond of this study, based on the pervious studies we can conclude that the likelihood of an accident and likelihood of transport of plume over

Turkey if an accident occurs are higher in Kozloduy NPP due to its more safety deficiencies and higher probability of the wind flow to Turkey from W, NW and N sectors.

2.3. Recommendations for Future Work

The study presented in this manuscript is the first study in our country to determine the potential effects of accidents that can occur in the neighboring countries. The modeling study was also performed for a potential accident in Akkuyu, although the probability of an accident is significantly smaller because of the newer technology that will be used, at least to get a feeling on how much health risk to population in this country will be affected if we decide not to built a nuclear power station in this country. The results clearly demonstrated that Kozloduy nuclear power station in Bulgaria poses a serious danger on the health of the population in our country.

Kozloduy is not the only nuclear power station around Turkey. There are other nuclear power plants in Armenia and Romania, which operate with similar old technologies. The health risks posed by these NPPs are unknown. Conducting similar studies with those NPPS and comparison of the results with results obtained in this study can result in more complete assessment of the risks posed by old-technology NPPS surrounding Turkey.

The methodology used in this study to determine and compare the risks due to the two NPPs is one of the available approaches. An alternative would be to estimate the highest and most probable risks due to accidents at every grid over the country. Such calculation could facilitate easier and more quantitative comparison between the effects of NPPs. This approach was not applied in this study because it would double the computation time, but appears to be a better way of risk assessment and should be used in future studies.

Individual risks and collective risks in this study were calculated for 12 cities selected as receptors. The selection of receptors was based on population. With the current selection it was necessary to use approximations when risks were extrapolated to regions and to whole country. A better approach would be to select receptors based on grids as well as population. This will increase the calculation time significantly, but also improve the uncertainties due to assumptions in extrapolating risks from cities to regions.

The health risks found in this study includes only late effects of radiation (fatal and non fatal cancer and hereditary effects), but do not include risks due to early effects, which refers to health problems that are observed immediately after the accidents. A calculation of early effects is more difficult and time consuming, as calculations should be performed for each organ separately. Such detailed calculations was beyond the scope of this preliminary study, but should be included in more comprehensive studies in the future

REFERENCES

1. AEA Technology, Harwell, 2001. "Review of Deposition Velocity and Washout Coefficient, ANNEX A".
2. Aktürk, 2001." General Energy Outlook of Turkey and Sustainable Enery Options".
3. Apsley, D. D., Carruthers, D. J., Singles, R., Mchung, C., Dyster, S., National Power, CERC. 2000. "Modeling Wet Deposition"
4. Baferstam U., 1995."Probabilistic Assessment of Doses and Depositions after a Hypothetical Accident at the Barseback Nuclear Power Plant Using 2 Years' Hourly Meteorological Data"
5. Baklanov A., Sorensen J.H., 2000. "Parameterization of Radionuclide Deposition in Atmospheric Long Range Transport Modeling".
6. Bayer, A., Bleher, M., Hornung-Lauxmann, L., König, K., Stapel R. 1988. "Prognoses for Contamination, Production-Location, Market Place, Total Diet, and Incorporation Measurements - Steps in the Investigation of Radiation Exposure to Man via the Ingestion Pathway in the Case of an Accident".
7. Boeck B., 1997. "Introduction to Severe Accident Especially the Containment Behavior "
8. Brandt, J., Christensen, J.H., Frohn, L.M. 2002 "Modeling Transport and Deposition of Cesium and Iodine from the Chernobyl accident Using the Dream Model"

9. Cao., J.Z., Yeung, M.R., Wong, S.K., Ehrhardt, J., Yu, K.N.,1999. ”Adaptation of COSYMA and Assessment of Accident Consequences for Daya Bay Nuclear power Plant in China”.

10. Commission of the European Communities, 2002. “Regular Report on Bulgaria’s Progress Towards Accession”.

11. Dayan, U. and Miller J. M., 1989. “Meteorological And Climatological Data From Surface and Upper Air Measurements For the Assessment of Atmospheric Transport and Deposition of Pollutants in the Mediterranean Basin: A rewiev.“ MAP Technical Report Series No 30.

12. Draxler, R.R., Hess G.D., 1997. “Description of the HySPLIT_4 Modelling System”

13. Draxler, R.R., Hess G.D., 1998. “An Overview of the HySPLIT_4 Modelling System for Trajectories, Dispersion and Deposition”.

14. Draxler, R.R., 1999. “HySPLIT _4 User’s Guide”

15. Enconet Consulting, 1997. “Current Status of Probabilistic Safety Assessment for Soviet Designed Reactors”.

16. European Union, 1998. “Real Way to Reduce Nuclear Risk in Eastern Europe”.

17. Evans, J.S., Moleller, D.W.,1988. “Radiological Health Effects Models For Nuclear Power Plant Accident Consequence Analysis.”

18. Fogh, C.L., Roed J., Kasper G.J. 1998. “Radionuclide Resuspension and Mixed Deposition at Different Heights”. *Journal of Environmental Radioactivity 46, 67-75.*

19. GESAMP ((IMO/FAO/Unesco/WMO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Pollution),1990. "The State Of The Marine Environment". UNEP Regional Seas Reports and Studies No.115.

20. Graggaber M., Pfanzagl B., Wenisch A., Seibert P., Lahodynsky R., 1998."Environmental Impact Assessment Khmelnitsky 2/Rovno 4"

21. Güllü G., Ölmez I., Aygün S., Tuncel G., 1998. "Atmospheric Trace Element Concentrations Over the Eastern Mediterranean Sea: Factors Affecting Temporal Variability." J. *Geophysical Research, 103,21943-21954.*

22. Hasemann, I. 2000. "Draft Rodos Report, Model Description of the Health Effects Modeling".

23. Hobbie, K., 1997."Intermediate Physics for Medicine and Biology ". 3rd edition.

24. ICRP Publication 23, 1974. "Report of the Task Group on Reference Man".

25. ICRP Publication 60,1990."Recommendations of the International Commission on Radiological Protection".

26. ICRP Publication 67, 1993. "Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 2 Ingestion Dose Coefficients".

27. International Atomic Energy Agency, 2000. "IAEA Safety Glossary". Version 1.0.

28. International Atomic Energy Agency, 1986. "IAEA –TECDOC-379, Atmospheric Dispersion Models for Application in Relation to Radionuclide Releases".

29. International Atomic Energy Agency, 1994. "IAEA-TECDOC-733, The

Utilization of Real Time Models as a Decision Aid Following a Large Release of Radionuclides into the Atmosphere”

30. International Atomic Energy Agency, 1997. “IAEA-TECDOC-955, Generic Assessment Procedures for Determining Protective Actions During a Reactor Accident”
31. Katsoulis, B. D. and Whelpdale D. M.,1993. “A climatological analysis of four day backtrajectories from Aliartos, Greece” *Theoretical and Applied Climatology*, 47, 93-103.
32. Kinser, A.M., Captain, USAF, 2001. “Simulating Wet Deposition of Radiocesium from the Chernobyl Accident”.
33. Kocher, D. C., 1983.“Dose Rate Conversion Factors for External Exposure to Fotons and Electrons.”
34. Kubilay, N. and Saydam A. C., 1995. “Trace Elements in the Atmospheric Particulates Over the Eastern Mediterranean; Concentrations, Sources and Temporal Variability”. *Atmospheric Environment,29,2282-2300.*
35. Mouchel Consulting Ltd, Tacis Nuclear Safety, 1998. “Environmental Impact Asessment for Rivne 4 NPP”
36. Lamarsh, J. R. 1983. “Introduction to Nucleer Enginnering”
37. Lo, C., Chen, I., Huang Y., Chou Y.2000 “Preliminary Study of the Emergency Planning Zone Evaluation for the Nuclear Power Plant in Taiwan by using MAACS2 Code”
38. Makhijani, A. 1996. “The Nuclear Power Deception”.
39. Martin, D. H. 2000.” Nuclear Awareness Project, Nuclear Threat in the Eastern Mediterranean, The Case Against Turkey’s Akkuyu Nuclear Plant”

40. Mouchel Consulting Ltd, 1998. Tacis Nuclear Safety, Environmental Impact Asessment for Rivne 4 NPP"

41. Nicolova, S., K.1998."Bulgaria Nuclear Plant, Economic Output and Environmental Impacts"

42. Nosske, D., Gerich, B., Langner, S., 1985. "Dosisfaktoren für Inhalation oder Ingestion von Radionuklidverbindungen."

43. Organization for Economic Co-operation and Development Nuclear Energy Agency (1998)."VVER Specific Features Regarding Core Degradation"

44. Organization for Economic Co-operation and Development Nuclear Energy Agency (2002). "Chernobyl/ Assessment of Radiological and Health Impact"

45. Paretzke, H.G., Stather, J.W., Muirhead, C.R., 1989. "Risk Factors for Late Somatic Effects".

46. Pasler J., 2000. "Description of the Atmospheric Dispersion Model ATSTEP"

47. Pecha, P., Kuca, P., Pechova, E., 2001. "Sensitivity Study of Influence of Input Parameters Variations for Removal Process Calculations on Activity Depletion in the Radioactive Plume and Deposition on the Ground". 7th Int. Conf. On Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes.

48. Petersen, R.A. and J.D. Stackpole, 1989."Overview of the NMC Production Suite Weather and Forecasting."4(313-322).

49. Rigina, O., Baklanov, A. 2001. "Regional Radiation Risk and Vulnerability Assessment by Integration of Mathematical Modelling and GIS Analysis" *Journal of Environmental International.* Vol 27, No.6.

50. Simmonds, J.R., Steinhauer, C., Haywond, S.M., 1987. " The Transfer of

Radionuclides Through Food Chains Following Accidental Releases to Atmosphere “.

51. Slaper H., Blaauboer R.O.,Eggink G.J. 1994. ”A Risk Assessment Method for Accidental Releases from Nuclear Power Plants in Europe”
52. Snell, V., G., 2001. “Severe Core Damage Accidents”
53. State Statistical Institute, 2000 Census Results.
54. Turai, I. 2000. “Deterministic and Stochastic Effects of Exposure to Ionizing Radiation. The Chernobyl Findings.”
55. Turkish Atomic Energy Authority, Nuclear Safety Department,2003. “Basic Safety Principles for Nuclear Power Plants”.
56. Wenisch, A. 1999. “Lecture on the Anti-Atom Symposium”.
57. World Meteorological Organization, 1985. “Atmospheric Transport of Contaminants into the Mediterranean Region” GESAMP Report 26, 53 pages.
58. UNSCEAR, 1988. “United Nations Scientific Committee on the Effects of Atomic Radiation. Sources, Effects and Risks of Ionizing Radiation, Annex D. Exposures From the Chernobyl Accident . New York: United Nations.”
59. U.S. Nuclear Regulatory Commission, 2000. “Regulatory Guide 1.183, Alternative Radiological Source Terms For Evaluating Design Basis Accidents At Nuclear Power Reactors”
60. U.S. NUREG 1150, Final Report, December 1990, Severe Accident Risk: An Assessment of U.S. Nuclear Plants.

APPENDIX A

NUCLEAR POWER PRIMER

Nuclear energy, inexhaustible supply of power, involves using the energy released from fusion of ^{235}U. The amount of energy available from uranium is many orders magnitude more than what is available from the equivalent amount of coal. 1 kg of uranium is the same as 16 metric tons of coal. Information in this Appendix has been provided from Lamarsh (1983).

A.1. Fission Process

Fission occurs when the nucleus of an atom, divides into two smaller nuclei leading to relatively more stable configurations. The heavier, unstable nuclei might therefore be expected to fission spontaneously, without external intervention. Such fissions rarely occur. In order for fission to occur rapidly enough to be useful in nuclear reactors, it is necessary to supply energy to the nucleus. When a neutron is absorbed, the resulting compound nucleus is formed in an excited state at energy equal to the kinetic energy of the incident neutron plus the separation energy or binding energy of the neutron in the compound nucleus. If this binding energy alone is greater than the critical energy for fission of the compound nucleus, then fission can occur with neutrons having zero kinetic energy. For example, when a neutron of zero kinetic energy is absorbed by ^{235}U, the compound nucleus, ^{236}U, is produced with more energy than its critical energy and fission can immediately occur. Nuclei such as ^{235}U that lead to fission following the absorption of a neutron called fissile. ^{233}U and ^{239}Pu are also fissile. Nuclei such as ^{238}U, which don't fission unless struck by an energetic neutron, are said to be fissionable but nonfissile. Nonfissile isotopes cannot alone be used to fuel nuclear reactors, and it is the fissile isotopes, especially ^{235}U and ^{239}Pu, that are the practical fuels of nuclear power.

Only one fissile nuclide, ^{235}U, is found in nature, where it occurs with an isotopic abundance of 0.72 %. Despite this low concentration of fissile isotope it is possible to fuel certain types reactors. However, most modern reactors require enriched uranium, that is, uranium in which the concentration of ^{235}U has been increased over its natural value.

A.2. Fission Chain Reaction

Nuclear energy is released by way of the fission chain reaction. In this process, neutrons are emitted by fissioning nuclei induce fissions in other fissile or fissionable nuclei, the neutrons from these fissions induce fissions in still other fissile or fissionable nuclei; and so on. Such a chain reaction can be described quantatively in terms of the multiplication

factor; k. This is defined as the ratio of the number of the fissions in one generation divided by the number of fissions in the preceding generation. In the equation from this is;

$$k = \frac{number\ of\ \ fissions\ in\ \ one\ generation^{n+1}}{number\ of\ \ fissions\ in\ preceding\ generation^{n}} \qquad \text{Eqn.A.1}$$

If k is equal to one, the chain reaction proceeds at a constant rate, energy is released at a steady level, and the system is said to be critical. If k is less than 1, the number of fission decreases with time and the chain reaction is called subcritical, if k is greater than 1, the system is said to be supercritical, which means the number of fission increases from generation to generation.

Devices that are designed so that the fission chain reaction can proceed in a controlled manner are called nuclear reactors.

To make a reactor critical, or otherwise to adjust the value of k, it is necessary to balance the rate at which neutrons are produced within the reactor with the rate at which they disappear.

A.3. Fission Products

Symmetric fission, a fissioning nucleus should split more or less in half is a rare event. Fission is almost asymmetric, so that the masses of the two fragments are substantially different. The fission product yield is the percent of the fission fragments produced with a given mass number and it is a function of the mass of the target atom. With the increasing energy of the incident neutron the fission becomes more symmetric.

When the fission products are initially formed, they are excessively neutron rich, that is, they contain more neutrons than are necessary for their stability. As a result they decay by emitting a sequence of β rays, which are accompanied by various γ rays. For example, the isotope ^{115}Pd (palladium-115) is produced directly in fission and decays by the chain.

The quantitative aspects of fission product decay are complicated by the fact that hundreds of different radioactive nuclides are produced in fission, each with its own characteristics half-life and decay mode.

The amount of energy in the reservoir of nuclear fuel is frequently expressed in terms of "full-power days," which is the number of 24-hour periods (days) a reactor is scheduled for operation at full power output for the generation of heat energy. The number of full power days in a reactor's operating cycle (between refueling outage times) is related to the amount of fissile ^{235}U contained in the fuel assemblies at the beginning of the cycle. A higher percentage of ^{235}U in the core at the beginning of a cycle will permit the reactor to be run for a greater number of full power days.

At the end of the operating cycle, the fuel in some of the assemblies is "spent," and it is discharged and replaced with new (fresh) fuel assemblies. The fraction of the reactor's fuel core replaced during refueling is typically one-fourth for a boiling-water reactor and one-third for a pressurized-water reactor.

The amount of energy extracted from nuclear fuel is called its "burn up," which is expressed in terms of the heat energy produced per initial unit of fuel weight. Burn up is commonly expressed as megawatt days thermal per metric ton of initial heavy metal.

A.4. Inside a Nuclear Power Plant

Nuclear energy is a form of energy derived from radioactive decay of uranium. Like almost all forms energy, what the radiation does is to generate heat. Heat is produced in a nuclear reactor when neutrons strike uranium atoms causing them to fission in a continuous chain reaction. The heat drives steam turbine, which generates electricity.

In the broadest sense; the core, central part of the nuclear reactor, contains the fuel, control mechanisims, the moderator and the coolant. The fuel includes the fissile isotope that is responsible both for criticality of the reactor and for the release of fission energy. Although nuclear fuel varies widely among different reactor types such as research reactors whose purpose are not to generate electricity but to perform research and to provide isotopes for medical or other purposes, use uranium metal fuel plates, the fuel for most reactors is produced from uranium dioxide powder, UO_2, which is a black ceramic material with high melting point of approximately 2800 ˚C. The UO_2 is in the form of small cylindrical pellets, about 1 cm in diameter and 2 cm long. The pellets are loaded in one sequence into metal tubes whose length is about 4m. The charged metal tubes are called fuel rods. Fuel rods are assembled into bundles called fuel elements or fuel assemblies, which are loaded individually into the reactor core. Control elements, which are made of materials that absorb neutrons like boron, determine the rate of fusion by regulating the number of neutrons. They are placed among the fuel assemblies. When the control elements, or control rods as they are often called, are pulled out of the core, more neutrons are available and the chain reaction speeds up, producing more heat. When they are inserted into the core, more neutrons are absorbed, and the chain reaction slows or stops, reducing the heat. The rods themselves may be cylindrical in shape or they may be sheets or blades. The coolant removes the heat generated by fission process. Water is the most common coolant, but pressurized water, helium gas and liquid sodium also are used. Slow neutron reactors operate on the principle that Uranium-

235 undergoes fission more readily with thermal or slow neutrons. Therefore these reactors require moderator for slowing neutrons from high speeds upon emerging from fusion reactions. The most common moderators are graphite (carbon), light water (H_2O) and heavy water (D_2O). Since slow neutron reactors are highly efficient in producing fission in Uranium-235, slow neutron reactors operate with natural or slightly enriched uranium. Many types of reactors have been proposed according to their coolant and moderator. These will be shortly discussed the next subsection except PWRs since they have been already explained broadly in Chapter 2.

The various reactor components described are all located within the reactor vessel, which if the components are under pressure, is called the pressure vessel. The reactor vessel and nuclear steam supply system are surrounded by radiation shielding in varying amounts, for the protection of plant personnel during normal operation. To protect the public from the consequences of a reactor accident, which involves the release of fission products from the reactor the entire reactor installation, is enclosed in a containment structure.

In all nuclear power plants, the fission energy released in the reactor is used to produce steam, either directly in the reactor itself or in auxiliary heat exchangers called steam generators. This system serves the same function as the steam boiler in a conventional fossil-fuel plant. For example the water in a PWR is maintained at a high pressure, approximately 15.5 MPa. At this pressure the water will not boil, at least to any great extent. Since the water does not boil in the reactor, the steam for the turbines must be produced external to the reactor. This is done in steam generator, which has pressurized water on the hot side. High pressure, heated coolant water from the reactor enters at the bottom and passes upward and then downward through several thousand tubes each in the shape of an inverted U. The outer surfaces of these tubes are in contact with lower-pressure and cooler feed water returning from the turbine condenser. Heat transferred from the hot water inside the tubes causes the feed water to boil and produce steam. The wet steam produced in the section where boiling occurs passes upward into a portion of the steam generator known as the steam drum section. Here the steam is dried in various moisture separators before exiting to the turbines.

Pressurizer is used to control the pressure in the reactor cooling system so that boiling does not occur in the reactor. The pressurizer also is used to act as a surge tank for the system taking up the level variations in the system. Heaters are installed at the bottom of the pressurizer for heating the water to 652F and 2250 pounds per square inch. Automated pressure control valves (called power operated relief valves) and safety valves, connected to the top of the pressurizer, can open to control and maintain pressure.

Secondary Systems are the non-radioactive parts of the nuclear power plants, where steam flows to the turbine, condenses in the condenser, then is pumped back to the steam generator first by condensate pumps, then by feedwater pumps. The feedwater heaters improve the efficiency of the cycle by recovering and reusing energy that would otherwise be lost.

Turbines, which are coupled to a generator to produce electricity, in principle are simple machines. They consist of a series of bladed wheels affixed to an axle, which rotates at high speed as steam at high temperature and pressure strikes the turbine blades. Steam is always delivered to a turbine as dry that means it shall not contain water as possible. Otherwise excessive erosion of the blades due to the liquid droplets cause reduced turbine lifetime.

All nuclear power plants have some form of emergency makeup water system in the event that normal makeup is lost and a major break occurs in the reactor cooling system. There are two phases considered:

(i) The injection phase when the pumps take a suction from a large tank and pump that water into the reactor cooling system or reactor, and

(ii) The recirculation phase when the pumps take suction from the containment sump, which is a vault to temporally store the drain water inside the reactor containment, after all of the water has been pumped into the containment.

A major function of the Emergency Core Cooling Systems is to provide makeup water to cool the reactor in the event of a loss of coolant from the reactor cooling system. This cooling is needed to remove the decay heat still in the reactor's fuel after the reactor is shutdown. This system, in some plants may have a second major function, which is to provide chemicals to the reactor and reactor-cooling system. Major components are pumps, water supplies and interconnecting piping. Pumps are high-pressure and low-pressure pumps. Water supplies include storage tanks, referred as refueling water storage tanks, whose water has to come from somewhere, containment sump which is used to keep recirculating the water through the reactor once the storage tanks are empty, accumulators, used in PWRs, which are big storage tanks connected to the reactor cooling system that have water pressurized with nitrogen.

Reactor Water Chemical Cleanup Systems are used in light and heavy water reactor designs. The function of this system is to remove undesirable radioactive materials from the reactor cooling system; this includes fission products and corrosion products and to add appropriate chemicals for corrosion control.

A.5. Types of Nuclear Reactors:

A.5.1. Light water Reactors:

Today, most commercial reactors used for generating electric power employ light water as both moderator and coolant.

(i)Boiling Water Reactors:

BWRs use water as both coolant and moderator. The uranium fuel must always be enriched like other light water reactors. Compared with the PWR, the reactor core cooling system is not a closed cycle system but functions as a steam producer. Unlike other reactors steam can go straight to the turbines that make electricity by allowing water within the reactor circuit to boil.

(ii)Graphite Moderated Boiling Water Reactors:

RBMK reactors, most prominently in Chernobyl, are boiling water reactors with a graphite moderator. The whole core cooling is separated in two loops, the reactor has no pressure vessel. The enriched uranium fuel is enclosed by many tubes, which are cooled by water from the core cooling system. The exchange of fuel rods takes place during operation. There is no full pressure containment shell, complete isolation is dependent on a pressure suppression system.

A.5.2. Gas Cooled Thermal Reactors

In the GCRs graphite is used as the moderator. The fuel is natural uranium, carbon dioxide gas is used as the coolant to remove the heat from the fuel elements. Hot gas from the reactor vessel goes to a steam generator similar to the one in pressurized water reactor.

Recent developed High Temperature Gas Cooled Reactor (HTGR) technology is considered an advanced nuclear energy source for the future. This is graphite moderated, helium cooled thermal reactor. Fuel for the HTGR is in the form of ceramic-coated small particles containing highly enriched uranium and thorium.

A.5.3. Pressurized Heavy Water Reactors

PHWRs use heavy water as the coolant and moderator, natural uranium as fuel. Hundreds of horizontal pressure tubes are used to contain the fuel and coolant rather than one large pressure vessel. These reactors are refueled while the reactor is in operation. Most common is Canadian designed power reactor, CANDU.

A.5.4. Breeder Reactors

This type of reactors is used not only to produce electricity but also to generate fuel. Surrounding the core of breeder reactor is a region of fertile material called the blanket. There are four types developed to date:

(i)Liquid Metal Cooled Fast Breeder Reactor

The coolant in this reactor is liquid sodium and the fuel is uranium-plutonium that needs fast neutrons to generate fission so moderator is not required to slow neutrons in this reactor.

(ii)Gas Cooled Fast Breeder Reactor

It is a helium-cooled reactor, fueled with a mixture of uranium and plutonium.

(iii)Molten Salt Breeder Reactor

The fuel and coolant are mixed together in one homogenous fluid, which is composed of various fluoride salts and graphite is used as moderator.

(iv)The Light Water Breeder Reactor

The water is used for both cooling and moderating purposes.

APPENDIX B

DATA RELATIVE TO CHAPTER 3

Table B.1. Reactor Inventories for the Reactors with Electrical Power of 440 and 1000 MW(t)

Nuclide	Group	VVER 440	PWR 1000
Am-241	La	3.18E+13	7.22E+13
Ba-140	Ba	2.45E+18	5.56E+18
Ce-141	Ce	2.37E18	5.39E+18
Ce-143	Ce	1.97E+18	4.77E+18
Ce-144	Ce	1.34E+18	3.05E+18
Cm-242	La	0.99E+16	2.26E+16
Cm-244	La	0.48E+15	1.09E+15
Co-58	Ru	1.61E+16	3.67E+16
Co-60	Ru	1.08E+16	2.46E+16
Cs-134	Cs	1.27E+17	2.89E+17
Cs136	Cs	0.49E+17	1.12E+17
Cs-137	Cs	0.77E+17	1.75E+17
I-131	I	1.342E+18	3.05E+18
I-132	I	1.94E+18	4.41E+18
I-133	I	2.644E+18	6.01E+18
I-134	I	3.036E+18	6.90E+18
I-135	I	2.37E+18	5.39E+18
Kr-85	Xe	0.906E+16	2.06E+16
Kr-85m	Xe	3.66E+17	8.32E+17
Kr-87	Xe	0.717E+18	1.63E+18
Kr-88	Xe	1.038E+18	2.36E+18
La-140	La	2.526E+18	5.74E+18
Mo-99	Ru	2.486E+18	5.65E+18
Nb-95	La	2.266E+18	5.15E+18
Nd-147	La	0.95E+18	2.16E+18
Np-239	Ce	2.697E+19	6.13E+19
Pr-143	La	2.046E+18	4.65E+18
Pu-238	Ce	0.999E+15	2.27E+15

Table B.1. Continued

Nuclide	Group	VVER 440	PWR 1000
Pu-239	Ce	3.621E+14	8.23E+14
Pu-240	Ce	3.621E+14	8.23E+14
Pu-241	Ce	0.607E+17	1.38E+17
Rb-86	Cs	3.96E+14	9.00E+14
Rh-105	Ru	0.81E+18	1.84E+18
Ru-103	Ru	1.72E+18	3.91E+18
Ru-105	Ru	1.188E+18	2.70E+18
Ru-106	Ru	4.246E+17	9.65E+17
Sb-127	Te	0.986E+17	2.24E+17
Sb-129	Te	0.528E+18	1.20E+18
Sr-89	Sr	1.421E+18	3.23+18
Sr-90	Sr	0.603E+17	1.37E+17
Sr-91	Sr	1.747E+18	3.97E+18
Tc-99m	Ru	2.16E+18	4.91E+18
Te-127	Te	0.946E+17	2.15E+17
Te-127m	Te	1.808E+16	4.11E+16
Te-129	Te	0.497E+18	1.13E+18
Te-129m	Te	0.832E+17	1.89E+17
Te-131m	Te	2.006E+17	4.56E+17
Te-132	Te	1.874E+18	4.26E+18
Xe133	Xe	2.578E+18	5.86E+18
Xe-135	Xe	0.541E+18	1.23E+18
Y-90	La	0.647E+17	1.47E+17
Y-91	La	1.786E+18	4.06E+18
Zr-95	La	2.332E+18	5.30E+18
Zr-97	La	2.306E+18	5.24E+18

Table B.2. Decay Constants and Dose Conversion Factors

Nuclide	Ingestion Sv/Bq	External Soil $Svs^{-1}/(Bqm^{-2})$	Inhalation Sv/Bq	External Air $Svs^{-1}/(Bqm^{-3})$	Decay(λ) s^{-1}
Am-241	5.90E-07	2.62E-17	1.4E-04	8.28E-16	5.09E-11
Ba-140	2.50E-09	1.89E-16	1.00E-09	2.66E-14	6.27E-07
Ce-141	7.80E-10	7.67E-17	2.4E-09	8.31E-15	2.47E-07
Ce-143	1.20E-09	2.85E-16	9.2E-10	3.39E-15	5.83E-06
Ce-144	2.3E-08	1.88E-17	1.00E-07	1.17E-14	2.82E-08
Cm-242	1.90E-08	8.63E-19	4.80E-06	8.09E-16	4.92E-08
Cm-244	3.10E-07	7.67E-19	7.60E-05	4.50E-18	1.21E-09
Co-58	9.7E-10	8.56E-16	2.90E-09	3.84E-18	1.13E-07

Table B.2. Continued

Nuclide	Ingestion Sv/Bq	External Soil Svs^{-1}/(Bqm^{-2})	Inhalation Sv/Bq	External Air Svs^{-1}/(Bqm^{-3})	Decay(λ) s^{-1}
Co-60	7.3E-09	1.98E-15	5.90E-08	4.38E-14	4.20E-09
Cs-134	2.00E-08	1.37E-15	1.30E-08	1.13E-13	1.07E-08
Cs136	3.00E-09	1.86E-15	2.00E-09	6.98E-14	6.10E-7
Cs-137	1.4E-08	2.35E-18	8.6E-09	7.17E-17	7.35E-10
I-131	1.3E-08	3.52E-16	8.1E-09	3.68E-16	9.98E-07
I-132	1.7E-10	2.04E-15	9.7E-11	1.04E-13	8.37E-05
I-133	2.6E-09	5.74E-16	1.5E-09	2.69E-14	9.26E-06
I-134	6.5E-11	2.31E-15	3.5E-11	1.20E-13	2.20E-04
I-135	5.6E-10	1.29E-15	3.10E-10	7.26E-14	2.91E-05
Kr-85	0	1.01E-17	0	2.28E-16	2.05E-09
Kr-85m	0	1.68E-16	0	7.23E-15	4.30E-05
Kr-87	0	7.71E-16	0	3.96E-14	1.51E-04
Kr-88	0	1.56E-15	0	9.86E-14	6.78E-05
La-140	2.3E-09	1.91E-15	1.30E-09	1.07E-13	4.79E-06
Mo-99	1.4E-09	1.74E-16	1.10E-09	7.17E-15	2.92E-06
Nb-95	6.9E-10	6.72E-16	1.60E-09	3.46E-14	2.29E-07
Nd-147	1.2E-09	1.38E-16	1.80E-09	5.90E-15	7.31E-07
Np-239	8.8E-10	1.67E-16	6.60E-10	7.36E-15	3.41E-06
Pr-143	1.3E-09	1.99E-17	2.20E-09	1.73E-16	5.92E-07
Pu-238	1.1E-07	7.96E-19	1.30E-04	4.03E-18	2.50E-10
Pu-239	1.2E-07	3.49E-19	1.4E-04	3.65E-18	9.14E-13
Pu-240	1.2E-07	7.64E-19	1.4E-04	3.96E-18	3.36E-12
Pu-241	2.4E-09	0	2.8E-06	0	1.53E-09
Rb-86	2.5E-09	1.55E-16	1.8E-09	4.72E-15	4.30E-07
Rh-105	4.00E-10	7.36E-17	2.6E-10	3.46E-15	5.45E-06
Ru-103	8.20E-10	4.34E-16	2.4E-09	2.11E-14	2.04E-07
Ru-105	2.9E-10	7.36E-16	1.20E-10	3.52E-14	4.34E-05
Ru-106	7.4E-09	0	1.3E-07	0	2.18E-08
Sb-127	1.90E-09	6.09E-16	1.6E-09	2.96E-14	2.08E-06
Sb-129	4.8E-10	1.25E-15	1.7E-10	6.53E-14	4.38E-05
Sr-89	2.5E-09	6.75E-17	1.1E-08	3.77E-16	1.59E-07
Sr-90	3.5E-08	1.38E-18	3.5E-07	9.16E-17	7.69E-10
Sr-91	8.4E-10	6.56E-16	4.5E-10	3.16E-14	2.03E-05
Tc-99m	1.7E-11	1.28E-16	8.8E-12	5.77E-15	3.20E-05
Te-127	1.9E-10	9.61E-18	8.6E-11	3.17E-16	2.06E-05
Te-127m	2.2E-09	6.09E-18	5.8E-09	1.40E-16	7.36E-08
Te-129	5.4E-11	1.06E-16	2.4E-11	2.96E-15	1.66E-04
Te-129m	2.9E-09	5.61E-17	6.5E-09	1.64E-15	2.39E-07
Te-131m	2.4E-09	1.23E-15	1.6E-09	6.47E-14	6.42E-06
Te-132	2.4E-09	2.15E-16	2.4E-09	9.51E-15	2.46E-06
Xe133	0	4.44E-17	0	1.55E-15	1.53E-06
Xe-135	0	2.53E-16	0	1.10E-14	2.11E-05
Y-90	2.9E-09	1.07E-16	2.3E-09	6.28E-16	3.00E-06
Y-91	2.6E-09	7.32E-17	1.3E-08	5.49E-16	1.37E-07
Zr-95	1.0E-09	6.50E-16	6.5E-09	3.33E-14	1.25E-07
Zr-97	2.3E-09	2.31E-16	1.2E-09	8.63E-15	1.14E-05

Table B. 3. Correction Factors Used in the Assessment

Correction	Deposition	Cloudshine	Grounshine	Ingestion
Am-241	1.00E+00	0	0	1.00E+00
Ba-140	1.00E+00	0	0	1.00E+00
Ce-141	1.00E+00	0	0	1.82E+00
Ce-143	1.00E+00	0	0	1.00E+00
Ce-144	1.00E+00	0	0	1.96E+00
Cm-242	1.00E+00	0	1.53E-16	1.01E+00
Cm-244	1.00E+00	0	0	1.05E+00
Co-58	1.00E+00	0	0	1.00E+00
Co-60	1.00E+00	0	0	1.00E+00
Cs-134	1.00E+00	0	0	1.00E+00
Cs136	1.00E+00	0	0	1.00E+00
Cs-137	1.00E+00	2.66E-14	5.39E-16	1.00E+00
I-131	1.00E+00	0	0	1.00E+00
I-132	1.00E+00	0	0	1.00E+00
I-133	1.00E+00	0	0	1.00E+00
I-134	1.00E+00	0	0	1.00E+00
I-135	1.00E+00	0	0	1.00E+00
Kr-85	0	0	0	1.00E+00
Kr-85m	0	0	0	1.00E+00
Kr-87	0	0	0	1.00E+00
Kr-88	0	0	0	1.00E+00
La-140	1.00E+00	0	0	1.00E+00
Mo-99	1.00E+00	0	1.28E-16	1.01E+00
Nb-95	1.00E+00	0	0	1.00E+00
Nd-147	1.00E+00	0	0	1.04E+00
Np-239	1.00E+00	0	0	1.02E+00
Pr-143	1.00E+00	0	0	1.00E+00
Pu-238	1.00E+00	0	0	1.00E+00
Pu-239	1.00E+00	0	0	1.00E+00
Pu-240	1.00E+00	0	0	1.00E+00
Pu-241	1.00E+00	0	0	1.03E+00
Rb-86	1.00E+00	0	0	1.00E+00
Rh-105	1.00E+00	0	0	1.00E+00
Ru-103	1.00E+00	0	1.03E-18	1.01E+00
Ru-105	1.00E+00	0	0	9.09E+00
Ru-106	1.00E+00	0	3.20E-16	1.00E+00
Sb-127	1.00E+00	0	9.61E-18	1.64E+00
Sb-129	1.00E+00	0	1.06E-16	1.00E+00
Sr-89	1.00E+00	0	0	1.00E+00
Sr-90	1.00E+00	0	0	1.07E+00
Sr-91	1.00E+00	0	0	2.86E+00
Tc-99m	1.00E+00	0	0	1.00E+00
Te-127	1.00E+00	0	0	1.00E+00
Te-127m	1.00E+00	0	9.61E-18	1.09E+00
Te-129	1.00E+00	0	0	1.00E+00
Te-129m	1.00E+00	0	0	1.01E+00
Te-131m	1.00E+00	0	4.57E-16	1.31E+00

Table B.3. Continued

Correction	Deposition	Cloudshine	Grounshine	Ingestion
Te-132	1.00E+00	0	2.04E-15	1.23E+00
Xe133	0	0	0	1.00E+00
Xe-135	0	0	0	1.00E+00
Y-90	1.00E+00	0	0	1.00E+00
Y-91	1.00E+00	0	0	1.00E+00
Zr-95	1.00E+00	0	0	1.00E+00
Zr-97	1.00E+00		1.28E-15	2.94E+00

Table B.4. Transfer Factors Used in this Assessment

	K_d (m^3t^{-1})	F_{milk} ($daykg^{-1}$)	F_{meat} ($daykg^{-1}$)	B_v vegetables	B_v cereals	B_v roots/ tubers	B_v grass
Am	700	2.0E-05	5.0E-04	1.0E-03	1.0E-03	1.0E-05	1.0E-03
Ba	60	4.0E-04	1.0E-04	1.5E-01	1.5E-01	1.5E-01	1.5E-01
Ce	850	2.0E-05	2.0E-03	1.0E-02	1.0E-02	1.0E-02	1.0E-02
Cm	2000	2.0E-05	2.0E-04	1.0E-03	1.0E-03	1.0E-05	1.0E-03
Co	45	2.0E-04	1.0E-02	1.0E-02	1.0E-03	1.0E-02	2.0E-03
Cs	1000	5.0E-03	3.0E-02	2.0E-02	2.0E-02	1.0E-02	1.0E-02
I	60	3.0E-03	1.0E-02	2.0E-02	2.0E-02	2.0E-02	2.0E-02
Kr	0	0	0	0	0	0	0
La	650	2.0E-05	2.0E-03	1.0E-02	1.0E-02	1.0E-02	1.0E-02
Mo	20	2.0E-03	7.0E-03	8.7E-02	6.0E-02	4.5E-01	6.0E-02
Nb	350	3.0E-03	3.0E-01	1.0E-02	1.0E-02	1.0E-02	1.0E-02
Nd	650	2.0E-05	4.0E-03	1.0E-02	1.0E-02	1.0E-02	1.0E-02
Np	300	5.0E-06	2.0E-04	1.0E-04	1.0E-04	1.0E-06	1.0E-03
Pr	650	2.0E-05	5.0E-03	1.0E-02	1.0E-02	1.0E-02	1.0E-02
Pu	4500	1.0E-07	3.0E-04	1.0E-04	1.0E-04	1.0E-06	1.0E-03
Rb	600	6.0E-03	1.0E-02	5.2E-03	3.6E-02	2.7E-01	3.6E-02
Rh	60	2.0E-03	0	1.5E-01	1.5E-01	1.5E-01	1.5E-01
Ru	350	1.0E-06	2.0E-03	7.5E-02	7.5E-02	7.5E-02	7.5E-02
Sb	450	2.0E-03	1.0E-03	2.0E-01	2.0E-01	2.0E-01	2.0E-01
Sr	35	2.0E-03	6.0E-04	5.0E-02	2.0E-01	8.0E-02	6.0E-02
Tc	15	1.0E-05	4.0E-02	1.0E+01	1.0E+01	1.0E+01	1.0E+01
Te	300	2.0E-04	8.0E-02	2.5E-02	2.5E-02	2.5E-02	2.5E-02
Xe	0	0	0	0	0	0	0
Y	500	1.0E-05	1.0E-03	1.5E-02	1.5E-02	1.5E-02	1.5E-02
Zr	3000	5.0E-06	2.0E-02	2.0E-04	2.0E-04	2.0E-04	2.0E-04

Table B.5. Plant Characteristics Used in This Assessment

	unit	grass	vegetables	cereals	Roots/tubers
S	kg/m^2	120	280	280	280
h	m	0.1	0.2	0.2	0.2
rho (ρ)	kg/m^3	1200	1400	1400	1400
Theta (θ)		0.25	0.25	0.25	0.25
$W_R+W_I-W_E$	m/day	1.1E-03	1.1E-03	1.1E-03	1.1E-03
Y_p	kg/m^2	7.4	3.8	0.72	4.6
λ_w	1/day	0.0496	0.0496	0.0496	0.0496
F_{ip}		0.25	0.3	0.05	0.3
t_{ap}	day	30	60	60	60

Table B.6. Diets as Used in this Assessment

	Delay-time t_d days	Consumption cow (fresh weight) kg/day	Consumption human kg/day	Preparation factor F_{bp}
Grass	0	85.5	0	1
Vegetables	0	0	0.641	0.5
Cereals	60	0	0.299	0.3
Roots	0	0	0.342	0.5
Milk	0	0	0.803	1
Meat	20	0	0.14	1
Soil	-	0.6	0	1

Table B.7. Fraction of Population Living in Urban Areas at the Receptors

Receptors	Total Population	Population Living in Urban Areas	$f_{popurban}$
Ankara	4,007,860	3,540,522	0.88
Konya	2,192,166	1,294,817	0.60
Samsun	1,209,137	635,254	0.53
Kocaeli	1,206,085	722,905	0.60
Balıkesir	1,076,347	577,595	0.54
İstanbul	10,018,735	9,085,599	0.91
İzmir	3,370,866	2,732,669	0.81
Manisa	1,260,169	714,760	0.57
Erzurum	937,389	560,551	0.60
Şanlıurfa	1,443,422	842,129	0.58
Adana	1,849,478	1,397,853	0.76
Antalya	1,719,751	936,330	0.54