Radio Active Pollution: Causes, Control and Consequences

Unit 5

Topic 2

School of Studies in Environmental Science (IGAEERE)
Jiwaji University,
Gwalior

Chapter 16

RADIOACTIVE POLLUTION AND CONTROL

Rehab O. Abdel Rahman, Ph.D.
Associate Professor of Chemical Nuclear Engineering,
Radioactive Waste Management Department,
Hot Laboratory and Waste Management Center,
Center, Atomic Energy Authority of Egypt, Inshas, Cairo, Egypt
Hot Laboratory Center, Atomic Energy Authority of Egypt,
P.O. 13759, Inshas, Cairo, Egypt
alaarehab@yahoo.com, karimrehab1@yahoo.com

Matthew W. Kozak, Ph.D.
Principal Consultant, INTERA, Inc
3900 S Wadsworth Blvd,
Suite 555 Denver, CO 80235, The USA
mkozak@intera.com

Yung-Tse Hung, Ph.D., P.E., DEE.
Professor, Department of Civil and Environmental Engineering,
Cleveland State University, Cleveland, Ohio
16945 Deerfield Dr., Strongsville, Ohio 44136, The USA
yungtsehung@yahoo.com, yungtsehung@gmail.com

Abstract

In this chapter, a brief introduction is presented to radioactive pollution and its management. Both natural and artificial sources of radiation are discussed with special attention to the relative importance of each source. In addition, radioactive isotope applications in tracing, radiography, insect control, food preservation, medical diagnoses, therapy, sterilization, and power generation are briefly described. Sources of radioactive pollution are identified including nuclear weapon tests, nuclear accidents, routine effluent release into the environment, and radioactive waste. Radioactive pollution prevention measures are presented including: treaties, regulations and standards, and technical methods to control pollution. The risk-informed regulatory process is briefly described, along with the technical methods to control radioactive wastes via site selection criteria, design of radioactive waste disposal facilities, and performance assessment.

Keywords: Radioactive pollution, radioactive waste, control measures, sources, regulations, radioactive applications, standards and disposal facilities.

1. Introduction

Radiation is omnipresent on Earth in the form of natural radiation. All living organisms are continuously exposed to radiation from a variety of sources. Scientific understanding of radiation and its effects on humans and the environment dates back almost a century to the pioneering work of Roentgen and Becquerel. Less than 40 years later, the first purified radioactive materials were produced by the Curies and within a decade of this discovery, scientists had split the atom. Since then, radiation has been used for diagnosing and treating medical problems, generating electricity, and in many other industrial, agriculture, and research applications.

Pollution is one of the major problems that face humanity; it occurs when a substance is released into the environment in a manner or in quantities that prevent the environment from effectively handling it, leading to detrimental effects on the ecosystem.[1] Protecting the environment from the effect of radioactive pollution has received a great deal of attention from both governments and individuals. Figure 1 represents the public perception of the importance of different pollution sources.[2]

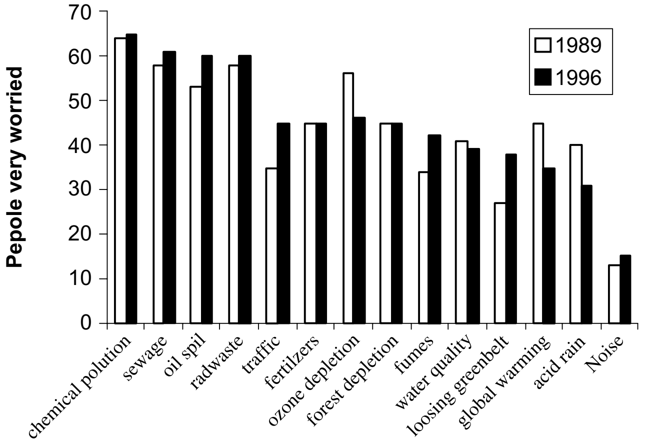


Figure 1. Public Awareness of the Importance of Different Pollution Sources.[2]

This chapter describes issues associated with radioactive pollution and control with special reference to the measures to control pollution from radioactive waste. Sources of radioactive pollution are identified and approaches to authorization and regulation to control radioactive pollution are presented.

1.1. *Radioactivity and Radiation*

The atom is the building block of matter; it consists of a small massive nucleus surrounded by a cloud of electrons. The nucleus is composed of positively charged protons and neutrally charged neutrons.[3] If the nucleus contains either excess neutrons or protons, the forces between these constituents will be unbalanced, leading to an unstable nucleus. An unstable nucleus will continually vibrate and will attempt to reach stability by undergoing radioactive decay. The major types of radiation emitted during radioactive decay include alpha particles, beta particles, gamma rays, and neutron radiation.[4]

1.1.1. *Alpha Particles* (α)

Alpha particles are energetic and positively charged helium nuclei consisting of two protons and two neutrons. The emission of these particles is comparatively rare in nuclides lighter than lead, but it is common for the heavier nuclides such as uranium-238, radium-226, and polonium-210. Even though these particles are highly energetic, their high mass leads to slow propagation through air, and they can be absorbed completely by paper or skin. Figure 2 represents the penetrating distance of different types of radiation.

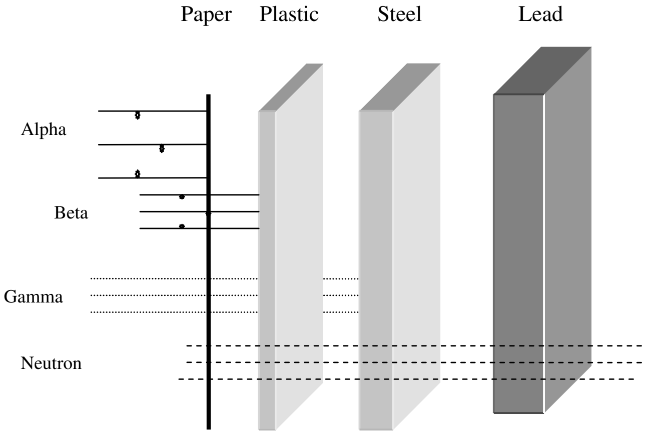


Figure 2. Penetration of Different Radiation Types.

1.1.2. *Beta Particles* (*β*)

Beta particles are fast-moving electrons emitted from the nucleus during radioactive decay. Two forms of beta decays exist. In the first, $^+\beta$ decay, one proton is transformed into a neutron and a positron and neutrino are emitted. In the second, $^-\beta$ decay, a neutron change into a proton and antineutrino are emitted. Human beings are exposed to beta particles from both artificial and natural radiation sources. Common radionuclides that produce significant beta radiation include tritium, carbon-14, and strontium-90. Beta particles are more penetrating than alpha particles: they can be completely absorbed by sheets of plastic, glass, or metal, as shown in Fig. 2. However, beta radiation is less damaging over equally traveled distances (Fig. 2).

1.1.3. *Gamma Rays* (*γ*)

Gamma rays are weightless packets of energy called photons, a form of high-frequency electromagnetic radiation. One source of gamma rays in the environment is naturally occurring potassium-40, which is present in the human body. Artificial sources include cobalt-60 and cesium-137. Gamma rays are very penetrating and only dense materials such as lead can provide good shielding from them (Fig. 2). Gamma rays can easily pass completely through the human body, with only a fraction absorbed by tissue.

1.1.4. *Neutron Radiation (n)*

Neutron radiation is a neutron emitted by an unstable nucleus, often fission and fusion. Neutrons are highly penetrating; when they interact with matter or tissue, they cause the emission of β and γ radiations (Fig. 2).

1.2. ***Radiation Units***

Absorbed dose (D) is defined as the amount of energy that ionizing radiation (ΔE) deposits in a unit mass of matter (Δm). It is expressed in gray (Gy), which is equal to 1 joule per kilogram.

Equivalent dose (H) is used to evaluate the relative biological effectiveness (RBE) of radiation to cause biological hazard. Biological hazard, for low doses of radiation, is defined as the risk of cancer mortality plus the risk of genetic effects. The International Commission on Radiation Protection (ICRP) has developed standard approaches for establishing the link between absorbed dose and effective dose. These standard approaches are periodically updated to reflect the best current understanding of the risk associated with radiation exposure. This means that the equivalent dose provides an index of the probability of hazard from exposure to different types of radiation. The SI unit of equivalent dose is Siveret (Sv), which is defined as the dose equivalent arising from an absorbed dose of 1 Gy. An older unit for the equivalent dose is rem (1 Sv = 100 rem), which is still widely used in several prominent nuclear countries, notably the United States and Russia.

The biological hazard of radiation to different parts of the human body varies from organ to another in both kind and magnitude. The effective dose is used to represent the overall biological hazard of radiation to a person as a single number; it is obtained by multiplying the equivalent dose by the organ weighting factor. The approach for determining the biological hazard of radiation is periodically updated.[5–7]

1.3. *Radiation Sources*

Radiation is a natural part of the environment. All living organisms, including human beings, are exposed to radiation daily. As a result, radiation exposures to radioactive pollution are incremental doses over the natural exposure. For the purposes of regulation of radioactive pollution, the incremental dose is often categorized as "artificial" radiation to distinguish it from "natural" background radiation. This distinction is adopted for the structure of this chapter, but it is noteworthy that there is no physical, chemical, radiological, or physiological differences between "artificial" and "natural" radioactivities. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) estimates that the annual dose average over the population of the world at the surface (mean individual dose in a population) is about 2.8 mSv. Of this value, 85% is from natural sources. The exposure to radon decay products at home represents about half of this value and the exposure of patients to radiation from medical uses accounts for another 14%. The remaining exposures are from a variety of different sources.[8] There is a degree of variation in this estimated mean value due to local conditions, including variation in radon decay products at home, altitude at which the person lives, and personal habits. These variations lead to annual doses of 10 mSv or more for local regions.[8] The percentage due to different radiation sources for mean individual dose is illustrated in Fig. 3.

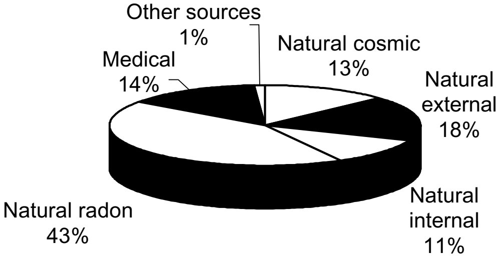


Figure 3. Relative Importance of Radiation Sources.[8]

1.3.1. *Natural Radiation*

Ionizing radiation and radioactive substances are natural and permanent features of the environment. Natural radiation comprises cosmic and terrestrial radiations.

1.3.1.1. Cosmic radiation

Cosmic radiation is produced when solar and galactic cosmic radiations collide with atoms of air (oxygen, nitrogen, and hydrogen) in the upper layers of the atmosphere to generate a complex set of secondary charged and uncharged particles, including protons, neutrons, pions, and lower-Z nuclei. These secondary particles generate more nucleons, producing a nucleonic cascade in the atmosphere. Figure 4 presents the contribution to dose equivalent rate from different cosmic ray components as a function of altitude.[9] From this figure, it is clear that at low altitude, muons represent the main source for exposure. As the altitude increases, the radiation exposure will be mainly due to neutrons, electrons/photons, and protons.

1.3.1.2. Terrestrial radiation

Terrestrial radiation is emitted by natural radioactive atoms present in natural materials such as soil, rocks, and clay. The predominant radioactive atoms in these materials include uranium, thorium, radium, and potassium. The decay of radium generates radon, a radioactive gas that is a high contributor to the overall terrestrial dose for many people.[10] When the building material or the surrounding soils

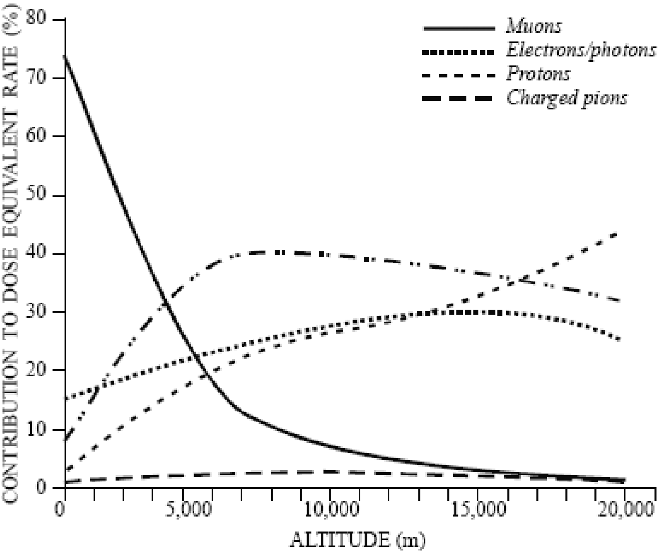


Figure 4. Components of the Dose Equivalent Rate Form Cosmic Rays in the Atmosphere.[9]

contain radium, radon gas produced from the radium can accumulate in the home; for homes with low air ventilation radon concentrations can be high and lead to significant radiation exposures.[11]

There are regions around the world where the concentrations of thorium, uranium, and other natural radionuclides in soil and beach sand exceed the average background levels by large margins. As examples, in the Brazilian coastal town of Guarapari and along the Kerala coast in India, the personal annual doses of members of the public may exceed the occupational annual dose limit of 20 mSv because of high levels of uranium and thorium in the local geology.[12–15]

1.3.2. *Artificial Radiation Source*

Artificial radiation sources are produced in a nuclear reactor or accelerator. These radiation sources are used in both medicine and industry. The main users of artificial radionuclides include medical facilities, such as hospitals and pharmaceutical facilities; research and teaching institutions; and nuclear fuel cycle facilities, such as power reactors, uranium mills, and fuel fabrication plants. Figure 5 illustrates the mean individual dose from different artificial and natural radiation sources.[3]

1.4. *Hazard of Radioactive Materials*

Radiation has sufficient energy to strip away electrons from atoms (creating two charged ions) or to break some chemical bonds. Living tissue can be damaged by ionizing radiation when it absorbs energy. The body attempts to repair the damage; however, sometimes the damage is of a nature that cannot be repaired or it is too severe or widespread to be repaired. Furthermore, mistakes made in the natural repair process can lead to cancerous cells. The biological effect of radiation can be classified according to the type of exposure.[16]

1.4.1. *Health Effects of Chronic Exposure*

Chronic exposure refers to long-term radiation exposure at a low to moderate level. This type of exposure leads to a probability of a health effect rather than to the certainty of a health effect; such conditions are known as *stochastic health effects*. The increased risk of developing cancer, cataracts, and genetic effects is considered among the possible stochastic effects. Genetic effects refer to damage to genetic material in a cell chromosome. Genetic effects can be ***somatic*** at which individual has experienced damage to some genetic material in the cell that could eventually cause the cell to become cancerous or ***hereditary*** in which the genetic effect is inherited or passed onto an offspring. These health effects have only been observed to occur at relatively high dose rates.

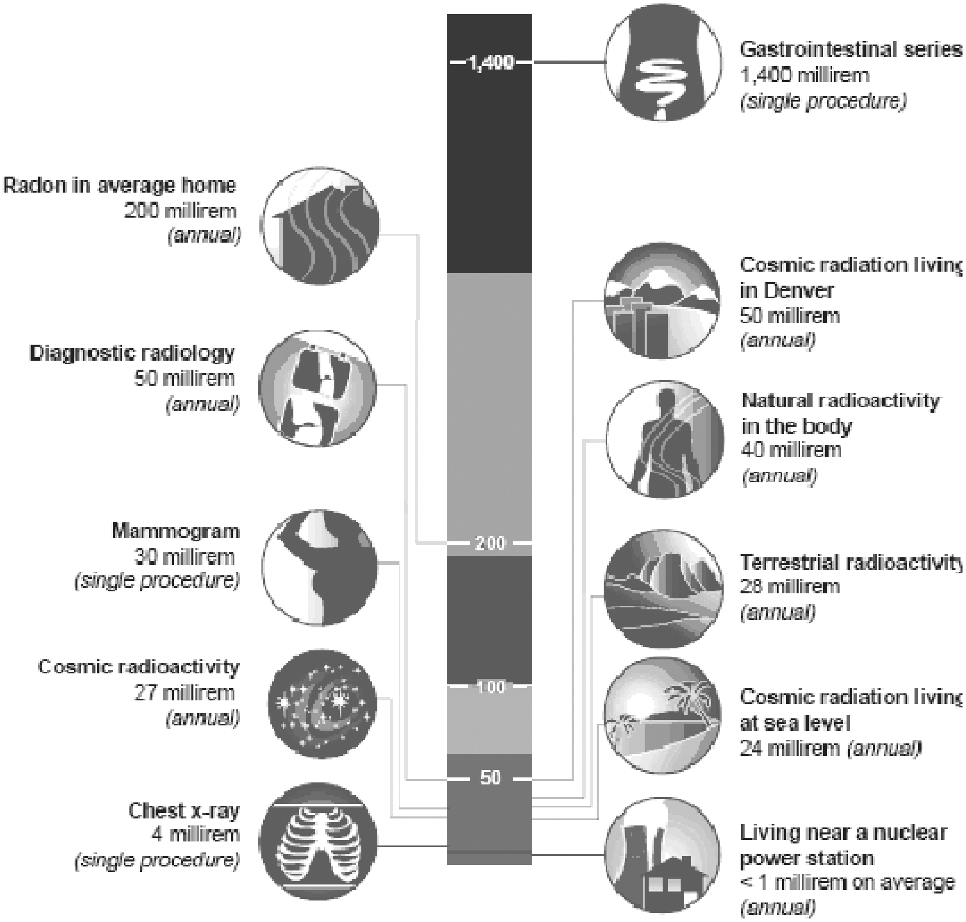


Figure 5. Relative Doses From Radiation Sources.[3]

The probability associated with stochastic health effects is too low to be observed at dose rates normally experienced by people, even for those who live in the regions of high background radiation. As a result, there is an assumption that the probability of health effects is linearly proportional to the absorbed dose, with no lower threshold below which no health effects occur. This assumption is commonly called the “linear, no threshold hypothesis” for risks associated with chronic exposure to radiation at very low doses. Increasing the exposure levels makes these health effects more likely to occur, but do not influence the type or severity of the effect. The “linear, no threshold hypothesis” has been the subject of some controversy in recent years, with some scientists suggesting the existence of a threshold below which radiation does not cause health effects, or is even beneficial (i.e. a hormetic effect at low absorbed dose).[17,18]

Table 1. Health Effect of Radiation Exposure.[17]

Exposure(rem)	Health Effect	Time to Onset
5–10	Changes in blood chemistry	
50	Nausea	Hours
55	Fatigue	
70	Vomiting	
75	Hair loss	2–3 Weeks
90	Diarrhea	
100	Hemorrhage	
400	Possible death	Within two months
1,000	Destruction of intestinal lining, internal bleeding, and death	1–2 Weeks
2,000	Damage to central nervous system, loss of consciousness, and death	Minutes, hours to days

1.4.2. *Health Effects of Acute Exposure*

Short-term and high-level exposure is referred to as acute exposure. Nonstochastic effects appear in acute exposure cases and become more severe, as the exposure increases. Acute health effects include burns and radiation sickness. Radiation sickness includes nausea, weakness, hair loss, skin burns, or diminished organ function. If the dose is fatal, death usually occurs within two months. Table 1 summarizes the health effects of radiation exposure.[19] For acute exposure at moderate dose rates the recovery is probable, includes the following possible effects: lowering of the white blood cell count, nausea, bacterial infections, vomiting, loss of appetite, reddening of the skin, diarrhea, fatigue, hair loss, and possible sterility. In a more severe exposure, the victim may suffer fever, abdominal pains, explosive diarrhea, internal bleeding, infection, shock, convulsions, coma, and ultimately death. Acute exposure is considered to be 250 mSv in 24 h.[20]

1.5. ***Technical Applications of Radioactive Materials***

1.5.1. *Radioisotope Tracing*

The concept of this technique is to replace one of the atoms in a molecule by a radioactive atom of the same element. Later, it is possible to trace the atom, as it undergoes physical or chemical transformations by observing the radiation emanating from it. To achieve the objectives of tracing, the physical form of the radiotracer is selected or manufactured so as to be consistent with the materials to be studied and its decay characteristics need to be appropriate.[21] Radioisotope tracing has proved to be effective in a number of different technical fields.

1.5.1.1. Environmental tracers

Radioisotope tracing plays an important role in detecting and analyzing pollutants, since even very small amounts of a radioisotope can easily be detected. Furthermore, through the use of rapidly decaying isotopes, experiments can be run leaving no residues in the environment. Nuclear techniques have been applied to a range of pollution problems including smog formation, sulfur dioxide contamination of the atmosphere, sewage dispersal from ocean outfalls, and oil spillage.[21]

1.5.1.2. Industrial tracers

By adding radioisotope tracers to materials used in various processes, it is possible to study the mixing and flow rates of a wide range of materials, including liquids, powders, and gases, and to locate leaks.[22] Tracers added to lubricating oils can help in measuring the rate of wear of engines, plant, and equipment. In addition, tracers have been used in plant operations to check the performance of equipment and improve its efficiency, resulting in energy savings and the better use of raw materials. In the oil and gas industries, unsealed radioactive solids (powder and granular forms), liquids, and gases are used to investigate or trace the movement of other materials, even within closed and otherwise inaccessible pipework and vessels.[23–26]

1.5.1.3. Fertilizers

Fertilizers labeled with radioactive isotopes, such as nitrogen-15 and phosphorus-32, provide a means of finding out how much fertilizer has been taken up by the plant and how much is lost.[27]

1.5.1.4. Application of radioisotopes tracing in water resources

Radioisotopes are used to trace and measure the extent of underground water resources. Such techniques provide important analytical tools in the management of existing supplies of water and in the identification of new and renewable sources of water. They provide answers to questions about origin, age, and distribution, the interconnections between ground and surface water, and renewal systems. The results permit informed recommendations for the planning and management of the sustainable use of these water resources. For surface waters, they can give information about leakage through dams, the dynamics of lakes and reservoirs, flow rates, and river discharge measurements and sedimentation rates.[28–30]

1.5.2. *Radiography*

Nondestructive testing (NDT) is commonly performed to provide quality assurance during engineering projects.[31] Gamma-emitting radioisotopes can be used to check welds of new gas and oil pipeline systems, with the radioactive source being placed inside the pipe and the film outside the welds. This is more convenient than employing X-ray equipment. Other forms of radiography (neutron radiography/autoradiography) can be used to gauge the thickness and density of materials, or to locate components that are not visible by other means (see Section 1.5.8).[32,33]

1.5.3. *Insect Control*

Crop losses caused by insects may amount to more than 10% of the total harvest worldwide; in some developing countries, the figure can be as high as 30%.[34] Chemical insecticides have for many years been humanity's main weapon in trying to reduce these losses, but they have not always been effective and can lead to toxic contamination of the foods they are intended to protect. Some insects have become resistant to the chemicals used and some insecticides leave poisonous residues on the crops. One solution has been the use of the sterile insects technique,[35] in which male insects are irradiated to sterilize them. Sterilized males are then released in large numbers in the infected areas. When they mate with females, no offspring are produced. With repeated releases of sterilized males, the population of the insect pest in a given area is drastically reduced.[36]

1.5.4. *Increasing Genetic Variability*

Ionizing radiation in plant breeding has been used for several decades to produce new genetic lines of sorghum, garlic, wheat, bananas, beans, avocado, and peppers; all of which are more resistant to pests and more adaptable to harsh climatic conditions.[37]

1.5.5. *Application of Radioisotopes in Food Preservation*

There is growing worldwide use of irradiation technology to preserve food. In almost 40 countries, health and safety authorities have approved irradiation of many kinds of food, ranging from spices, grains, and grain products to fruit, vegetables, and meat.[38] Following three decades of testing, a worldwide standard was adopted in 1983 by a joint committee of the World Health Organization (WHO), Food and Agriculture Organisation of the United Nations (FAO), and International Automic Energy Agency (IAEA).[39] In addition to reducing spoilage after harvesting, increased use of food irradiation is driven by concerns about food-borne diseases as well as growing international trade in foodstuffs, which must meet stringent standards of quality. Radiation is also used to sterilize food packaging. In the Netherlands, for example, milk cartons are freed from bacteria by irradiation.[40]

1.5.6. *Application of Radioisotope in Medicine*

Radiation and radioisotopes are used extensively in medicine, particularly diagnostically and therapeutically, for various medical conditions. Nuclear medicine mostly uses radioisotopes that emit gamma rays from within the body. It is estimated that about one out of every three hospital patients benefits in some way from the use of nuclear medicine.[41]

1.5.6.1. Medical diagnosis

Radioisotopes are an essential part of diagnostic treatment. In combination with imaging devices and computers, they are also used to study the dynamic processes taking place in the various organs. The procedure of medical diagnoses is based on giving a radioactive dose to the patient, then monitoring the activity in the studied organ. The organ can then be illustrated either as a two-dimensional picture or, with a special technique called tomography, as a three-dimensional picture. The most widely used diagnostic radioisotope is technetium-99 m, with a half-life of 6 h, and which gives the patient a very low radiation dose. Such isotopes are ideal for tracing many bodily processes with the minimum of discomfort and dose for the patient. They are widely used to indicate tumors and to study the heart, lungs, liver, kidneys, blood circulation and volume, and bone structure.[42,43]

A major use of radioisotopes for diagnosis is in radioimmunoassays for biochemical analysis. They can be used to measure very low concentrations of hormones, enzymes, hepatitis virus, some drugs, and a range of other substances in a sample of the patient's blood. The patient never comes in contact with the radioisotopes used in this diagnostic test.

1.5.6.2. Therapy

The uses of radioisotopes in therapy are comparatively few, but important. Iridium-192 implants in the form of a wire are used to give precise doses to limited areas. Iodine-131 is used to treat the thyroid for cancer and other conditions. Some cancers are treated using gamma rays from an external cobalt-60 source, others using internal beta radiation. A new treatment uses samarium-153 complexed with organic phosphate to relieve the pain of secondary cancers lodged in bone.[44,45]

1.5.6.3. Sterilization

Many medical products today are sterilized by gamma rays from a cobalt-60 source.[46] Since this technique does not require the application of heat, it is widely used in sterilizing a range of heat-sensitive items such as powders, ointments, and solutions and biological preparations such as bone, nerve, and skin used in tissue grafts. Medical products sterilized by radiation also include disposable syringes, cotton wool, burn dressings, surgical gloves, heart valves, bandages, plastic and rubber sheets, and surgical instruments.[47]

1.5.7. *Application of Radioisotope in Smoke Detectors*

One of the most common uses of radioisotopes is in smoke detectors. These contain a small amount of americium-241, which is a decay product of plutonium-241 originating in nuclear reactors. The americium-241 emits alpha particles, which ionize the air and allow a current to flow between two electrodes. If smoke enters the detector, it absorbs the alpha particles and interrupts the current, setting off the alarm.

1.5.8. *Application of Radioisotope in Instruments*

Gauges containing radioactive sources are in wide use in all industries where levels of gases, liquids, and solids must be checked.[48] These gauges are most useful where heat, pressure or corrosive substances, such as molten glass or molten metal, make it impossible or difficult to use direct contact gauges. Radioisotope thickness gauges are used in the making of continuous sheets of material including paper, plastic film, metal, etc., when it is desirable to avoid contact between the gauge and the material.

Density gauges are used where automatic control of a liquid, powder, or solid is important, for example, in detergent manufacture. Radioisotope instruments have three great advantages[48]:

1. Measurements can be made without physical contact with the material or product being measured.
2. Very little maintenance of the isotope source is necessary.
3. The cost/benefit ratio is excellent — many instruments pay for themselves within a few months through the savings they allow.

1.5.9. *Power Sources*

When radiation is absorbed, the radiated energy appears in the form of heat. A portion of this heat can be converted into electrical energy. Devices based on this principle are used for heart pacers and to power navigation beacons and satellites. The decay heat of plutonium-238 has powered many space vehicles and enabled voyager to send back pictures of distant planets. Plutonium-238 powered the Cassini space probe on its way to Saturn.[49]

2. Radioactive Pollution

The many applications of radioisotopes for industrial, medical, and power production inevitably lead to the releases of some of those radioisotopes into the surrounding environment. These releases may be categorized as either (1) planned releases that are a normal part of the application of the technology or (2) unplanned or uncontrolled releases associated with accidents. In the case of routine releases to the environment, each practice is evaluated to assure that the benefits outweigh the detriment,[50] and that the health risks from the routine release are negligible. For accidental releases, governmental authorities use action levels to determine when cleanup activities are required to protect the public health.[50]

Radioactive pollution arises from the discharge of radionuclides to the environment by nuclear power facilities, military establishments, research organizations, hospitals, and general industry. In addition, historical tests of nuclear weapons in the atmosphere and underground, nuclear and radioactive accidents, and the deliberate discharge of radioactive wastes from nuclear and other installations represent sources for radioactive pollution. Such radionuclides have the potential to find their way from air and water onto the ground and into the food chain.

2.1. *Sources of Radioactive Pollution*

2.1.1. *Military Activities and the Production, Testing, and Use of Nuclear Weapons*

The manufacture of nuclear weapons involves handling, transport, and storage of large quantities of radioactive materials. Weapons testing may involve the release of fission and activation products into the environment, and has in the past involved the deliberate dispersal of radioactive materials in the environment through atmospheric weapons testing.[51]

Atmospheric testing of nuclear weapons has been the most significant worldwide radioactive pollution source. This practice continued from 1945 to 1990 in various countries. The annual deposition of strontium-90 in different countries from the atmospheric tests is illustrated in Fig. 6. From this figure, it is obvious that the contribution of the test program of the United States dominated before 1958; then from 1959 to 1967, the dominant deposition of ^{90}Sr was contributed from the Soviet Union program. From 1968 to 1988, the deposition was primarily from the Chinese tests.

Nuclear weapons tested above the ground propelled a variety of radionuclides from tritium to plutonium into the upper atmosphere. From there, the radionuclides transferred slowly to the lower atmosphere and then to the earth's surface. Globally, the most important radionuclides from this source in terms of human exposure are now carbon-14, strontium-90, and cesium-137. Minute quantities of these are ingested with food and drink. Residual activity from radionuclides in the ground that emit gamma rays also causes a slight increase in human exposure. Internal and external irradiations contribute about equally to global average effective dose of 0.005 mSv in a year. This compares with a peak of more than 0.1 mSv in 1963. The global collective dose from weapon tests fallout is now about 30,000 man Sv annually, assuming a world population of 6,000 million.[51]

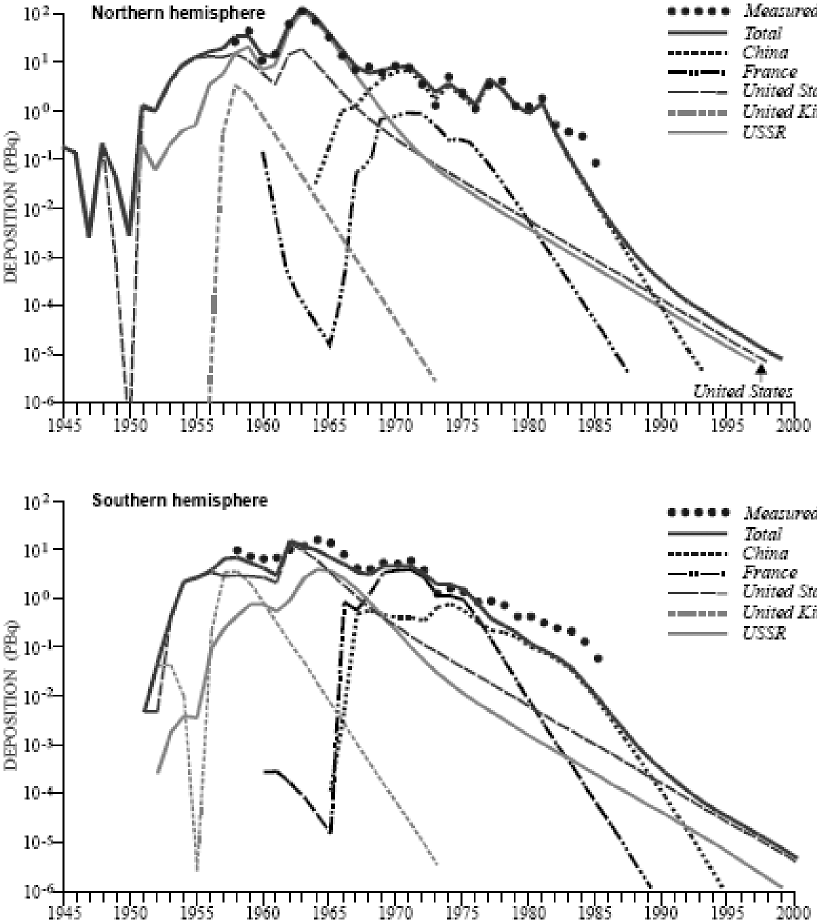


Figure 6. Components of Strontium-90 Deposition From Test Programs of Countries Calculated From Fission Yields of Tests With the Atmospheric Model.[50]

In addition to atmospheric testing, nuclear weapons were also tested underground in several countries, with the most recent of these tests conducted in 1998. Underground testing resulted in only localized releases of radionuclides to the environment, and significantly reduced the exposure of the population compared to atmospheric testing. Figure 7 represents the number and yield of underground and atmospheric nuclear weapon tests.[53]

Besides nuclear weapons tests, the military fuel cycle has also resulted in the releases of radioactive materials to the environment. These releases are localized at the manufacturing facilities in countries constructing nuclear weapons, but have led to significant local contamination in locations such as Hanford, the United States, and Chelyabinsk, Russia.[54,55]

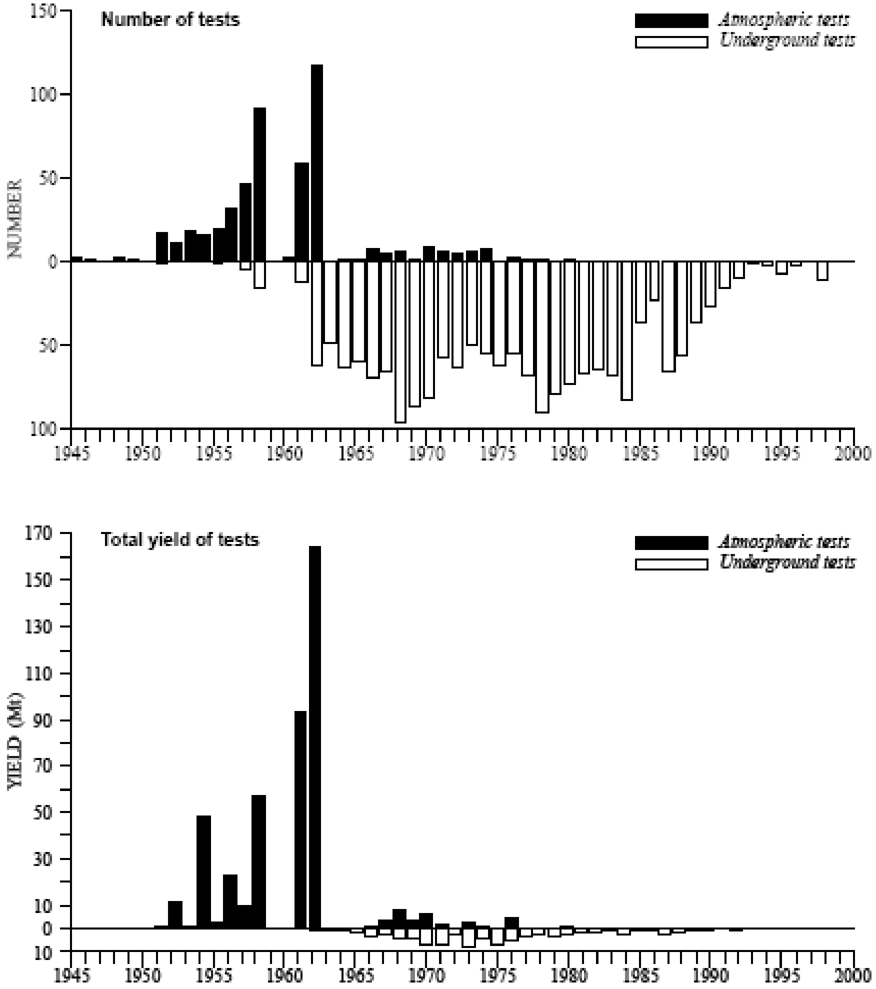


Figure 7. Test of Nuclear Weapons in the Atmosphere and Underground.[50]

Depleted uranium has been used for projectile weapons during recent conflicts.[56] This weapon is in a concentrated metallic from, and there have been concerns expressed by the public about elevated levels of radioactivity in the environment due to spent munitions. Depleted uranium can potentially have both chemical and radiological toxicities to the kidneys and the lungs. Health effects are determined by the physical and chemical natures of the depleted uranium to which an individual is exposed, and to the level and duration of exposure.[57,58] The WHO calculated the amount and fate of depleted uranium deposited at an "average" attack site in Kosovo.[59] The calculations showed that, if all the depleted uranium munitions expended during an attack remained within a kilometer, the increase of uranium in the soil would be 5%. The contribution of depleted uranium from military use to background radiation dose in Kosovo is within the natural variations found for background levels.[59]

2.1.2. *Nuclear and Radioactive Accidents*

Accidents involving the releases of radionuclides to the environment have occurred in power production, nuclear weapons production, and industrial applications. In the course of nuclear weapons production and transport, there have been several severe accidents resulting in considerable contamination.[60–63] These include Windscale Pile 1 (1957), Kyshtym (1957),[55] Palomares (1966), and Thule (1968).

The 1986 fire at the Chernobyl reactor led to widespread contamination. Airborne material was dispersed throughout Europe from the site in Ukraine. As the contaminated air spread throughout Europe and beyond, local weather conditions largely determined where the radionuclides were to fall. Rainfall caused more radionuclides to be deposited in some areas rather than others. The impact of the accident on the workers has involved an enormous number of people. The accident caused the deaths within a few days or weeks of 30 power plant employees and firemen (including 28 deaths that were due to radiation exposure), brought about the evacuation of about 116,000 people from the areas surrounding the reactor during 1986, and the relocation, after 1986, of about 220,000 people from Belorussia, the Russian Soviet Federated Socialist Republic (RSFSR) and the Ukraine.[64–67] However, health effects associated with the radioactive contamination itself have been small, and the primary health-related impacts of the accident were associated with the stress from the relocations.[68]

On 11 March 2011, a massive earthquake followed by a tsunami hit Fukushima Daiichi nuclear power station. The site includes 4 boiling water reactors (BWR) with Mark 1 containment. The site lost its external power due to the earthquake. It was planned to use emergency diesel generators to secure the power supply. However, these generators, the electric equipment rooms, and outdoor sea water pumps were submerged by the tsunami and lost their ability to function. As a result, the reactor experienced a loss of coolant, and it was necessary to inject seawater to maintain temperatures. Hydrogen accumulated in the containment building leading to explosions at the site. To achieve cold shutdown conditions, large amounts of water were injected into the reactors. The injected water leaked through the reactor pressure vessel and primary contaminant vessel into the basement of the building. Efforts were directed to minimize the accumulation of water, and to reuse the contaminated water for injection into the reactor. The radiation dose rate increased rapidly during the accident, and it has been in a stable declining trend since. It is now approximately at background levels. Three phases are planned for site remediation. The first is the removal of fuel from the spent fuel pools. The second is envisioned to take place over 10 years and aims to remove the fuel debris. The third stage comprises decommissioning, which is expected to end within 30 to 40 years.[69]

An accident involving loss of control of spent radiation sources occurred in Goiânia (1987). Four people died and six received doses of a few Gy from an abandoned and ruptured highly radioactive Cs-137 source.[70]

2.1.3. *Routine Release of Effluent to the Environment*

Nuclear electrical generation has grown steadily from the start of the industry in 1956. The relatively rapid rate of expansion that occurred from 1970 to 1985, an increase in energy generation of more than 20% per year, slowed to a pace averaging just over 2% per year from 1990 to 1996.[71] At the end of 1997, there were 437 nuclear reactors operating in 31 countries. The total installed capacity was 352 GW and the energy generated in 1997 was 254 GW. It is projected that nuclear energy will continue to supply about 17% of the total electrical energy generated in the world, as at present, or possibly a few percentage less. The nuclear fuel cycle includes mining and milling of uranium ore and its conversion to nuclear fuel material; the fabrication of fuel elements; the production of energy in the nuclear reactor; the storage of irradiated fuel or its reprocessing, with the recycling of the fissile and fertile materials recovered; and the storage and disposal of radioactive waste (Fig. 8).[72] At each stage of the nuclear fuel cycle, a variety of radionuclides are released in the form of liquid, gas, or solid particles. The nature of the effluent depends on the particular operation or process. Normalized releases and the resultant doses from each stage are presented in Fig. 9.[72]

2.1.3.1. Nuclear fuel cycle

Various stages of the nuclear fuel cycle and the operation and decommissioning of nuclear reactors all have the potential to create contaminated sites. The contamination may include mill tailings; spillage of ore end product at the mine and in transport; waste from enrichment and fuel fabrication operations; fission product and actinide waste streams from reprocessing of fuel elements; radioactive effluents from normal operations of nuclear power plants; wastes produced during decommissioning of reactors; and major releases under accident conditions.

2.1.3.2. Production and use of radioactive substances for medical, research, or industrial purposes

Radioactive materials have been used widely since their discovery for a variety of scientific, medical, and industrial uses. In some cases, either through ignorance, carelessness, or accident, sites have been left contaminated with residues of the

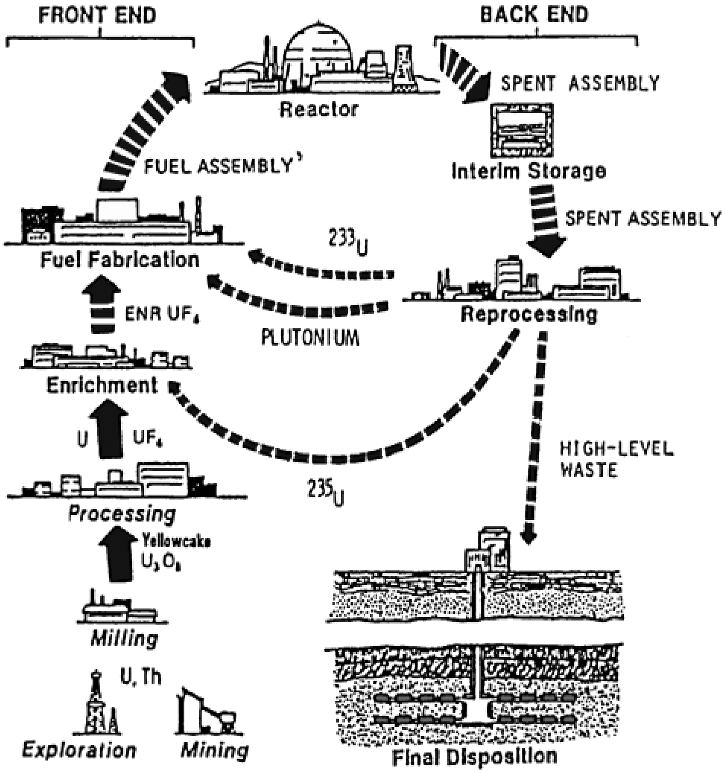


Figure 8. Nuclear Fuel Cycle.

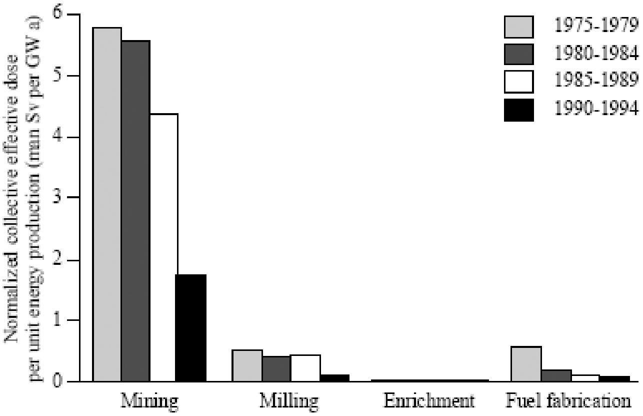


Figure 9. Normalized Collective Effective Dose Per Unit Energy Production for Mining, Milling, Enrichment, and Fuel Fabrication.[66]

Table 2. Activities That May Lead to NORM Contaminated Residues and Sites.[75]

Mineral Ores and Extracted Materials		Other Processing/Manufacturing
Copper	Titanium	Water treatment
Aluminum (bauxite)	Tungsten	Sewage treatment
Fluorspar	vanadium	Spas
Gypsum	Zircon	Paper and pulp
Iron	Coal (and coal ash)	Ceramics manufacture
Molybdenum	Oil and gas	Paint and pigment manufacture
Phosphate	Geothermal energy	Metal foundry
Phosphorous	Uranium and thorium	Optics
Potassium		Incandescent gas mantles
Precious		Refractory and abrasive sands
Rare earth		Electronics manufactures
Tin		Building materials

operations. Such sites include factories where radium was used in luminescent paint and thorium was used in thorium-coated gas mantles.[73]

2.1.4. *Radioactive Waste and Contaminated Areas With Naturally Occurring Radioactive Material (NORM) and Technically Enhanced NORM (TE-NORM)*

Because uranium and thorium are present in many ores containing other useful minerals, the mining of these ores and the processing to recover materials such as copper, gold, niobium, coal, and monazite will generally produce waste streams containing significant amounts of radioactivity. These have the potential to result in unacceptably contaminated sites.

Large areas have been contaminated in various parts in the world with radionuclides as a result of various human activities. Table 2 illustrates some activities that lead to NORM and TENORM contaminated residues and sites.[74,75] In cases where the level of contamination is high, measures might be needed to ensure that the area is safe to people to live or use for other purposes. For small areas, it might be possible to do this by removing contaminated soil and other materials, but for large areas, the amount of material would be too large. Other ways of protecting people include restriction on access to or use areas.

2.2. ***Prevention of Radioactive Pollution***

Governments are responsible for protecting the public and environments; the manner in which this responsibility is implemented varies from country to country. In this section, the international agreements and declarations approved from various countries are presented, and the guidelines to authorize and regulate radioactive effluent release is summarized. The technical methods to control the pollution are also reviewed.

2.2.1. *International Agreements and Declarations*

Radioactive effluent releases are subject to several international agreements and declarations, which may impose obligations on national policies and procedures. The aim from these agreements and declarations is to prevent the occurrence of radioactive pollution from effluent release. The International Convention on Nuclear Safety[76] and the Joint Convention on the Safety of Spent Nuclear Fuel Management and on the Safety of Radioactive Waste Management,[77] which are signed and ratified by numerous united nation member states, are examples of such agreements and declarations. Member states of the European Community are legally bound by the provisions of the Euratom treaty[78] and the discharge in the north-east Atlantic is controlled by the OSPAR convention.[79]

2.2.1.1. International convention on nuclear safety[72]

The Convention on Nuclear Safety was adopted in 1994 and entered into force in 1996. The nuclear safety targets are contained in the articles of the convention and the mechanism for improving safety is through the peer pressure exerted upon each other by the contracting parties at the regular review meetings. With regard to the controlled release of effluents from nuclear power plants, Article 15 (Radiation Protection) of the convention requires that:

> Each contracting party shall take appropriate steps to ensure that in all operational states the radiation exposure to the workers and the public caused by a nuclear installation shall be kept as low as reasonably achievable and that no individual shall be exposed to radiation doses which exceed prescribed national dose limits.

2.2.1.2. Joint convention on the safety of spent nuclear fuel management and on the safety of radioactive waste management[77]

Several articles of the joint convention address issues related to discharges. The principal reference is in Article 24 (Operational Radiation Protection); Part 2 requires that:

> Each contracting party shall take appropriate steps to ensure that discharges shall be limited:
>
> (i) to keep exposure to radiation as low as reasonably achievable, economic and social factors being taken into account and
> (ii) so that no individual shall be exposed, in normal situations, to radiation doses which exceed national prescriptions for dose limitation which have due regard to internationally endorsed standards on radiation protection.

In this context, discharges are defined as planned and controlled releases into the environment, as a legitimate practice, within the limits authorized by the regulatory body, of liquid or gaseous radioactive materials, that originate from regulated nuclear facilities during normal operation. However, in addition, under Articles 6 and 13 on siting, each contracting party is required to

> "consult contracting parties in the vicinity of such a facility, insofar as they are likely to be affected by that facility, and provide them, upon their request, with general data relating to the facility to enable them to evaluate the likely safety impact of the facility upon their territory."

2.2.1.3. Euratom treaty[78]

At the time of signature of the Euratom Treaty in 1957, its main objective was to contribute to the raising of the standard of living in the Member States and to the development of relations with the other countries by creating the conditions necessary for the speedy establishment and growth of nuclear industries. This role is achieved by conferring to the Community far reaching competence to ensure the availability of nuclear materials for civil purposes (ownership of fissile material, safeguards), access to research and technical information, and investment funds. In addition, the development of nuclear industry should be conditioned by the establishment of uniform safety standards to protect the health of workers and the general public, the application of which shall be ensured by the community. Article 2 (b) of the EURATOM treaty provides for establishment within the community of

> "... uniform safety standards to protect the health of workers and of the general public"

and for the community to

> "... ensure that they [the standards] are applied."

Article 37 Euratom

> "... provide the commission with such general data relating to any plan for the disposal of radioactive waste in whatever form as will make it possible to determine whether the implementation of such plan is liable to result in the radioactive contamination of the water, soil or airspace of another Member State."

2.2.1.4. OSPAR convention for the protection of the marine environment of the North–East atlantic[79]

During the ministerial meeting of OSPAR in Sintra, Portugal, in 1998, the ministers and the member of the European Commission emphasized that:

> Our commitment to take all possible steps to achieve our overall objective for the protection of the marine environment of the North East Atlantic of preventing and eliminating pollution, protecting human health and ensuring sound and healthy marine ecosystems, and commit ourselves to pursuing this goal through the following actions to produce a sustainable approach

> to the marine environment of the OSPAR maritime area and thus protect this inheritance for the new millennium.

In addition, the ministers reemphasized, "the clear commitments to the application of the precautionary principle and the polluter-pays principle and to the identification of Best Available Techniques (BAT) and Best Environmental Practice (BEP), including, where appropriate, clean technology." This statement includes a part on radioactive substances, emphasizing the willingness of the ministers to ensure the implementation of the above-mentioned Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) strategy with regard to radioactive substances.

2.2.1.5. The Rio de Janeiro conference and the precautionary principle[80]

The Rio Declaration on Environment and Development states in Principle 15 — the Precautionary Approach:

> In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.

In the framework of Agenda 21, the precautionary principle is to be applied in cases of potential irreversible impacts on the environment with relative high consequences (implying that these consequences are unacceptable).

2.2.2. *Radioactive Effluent Discharge Standards*

2.2.2.1. IAEA safety standards

IAEA issues safety standards covering nuclear, radiation, transport, and waste safeties. Concerning the control of discharge, the principal requirements are contained in the International Basic Safety Standards for Protection (BSS) against Ionizing Radiation and for the Safety of Radiation Sources.[81] The BSS translates the basic radiation protection recommendations of the International Commission on Radiation Protection (ICRP) into regulatory form. The essential requirement is that:

> Registrants and licensees shall ensure that radioactive substances from authorized practices and sources not be discharged to the environment unless: discharge should be within the discharge limits authorized by the Regulatory Authority; discharges should be controlled; public exposures committed by the discharges should be limited; and control of the discharges should be optimized in accordance with the Principal Requirements of the Standards.

Detailed guidance on setting discharge authorizations is contained in a safety guide named "Regulatory Control of Radioactive Discharges to the Environment."[82]

This safety guide outlines the responsibilities of the regulatory body and of the organization intending to discharge radioactive material, sets out the steps to be followed in setting a discharge authorization for a new practice, and gives advice on actions to be taken in cases of noncompliance and on the procedures to be followed for existing discharge practices.

2.2.2.2. EU basic safety standards directive (96/29 Euratom)

The revised Radiation Protection Ordinance sets a dose limit of 1 mSv for members of the general public. Additional limits for doses resulting from radioactive discharges and emissions from nuclear installations are specified for aerial and liquid releases each: individual effective dose and partial body dose for gonads, uterus, and red bone marrow should not exceed 0.3 mSv/y and partial body dose of all organs and tissues unless under 2 and 4 should not exceed 0.9 mSv/y where the partial body of bone surface and skin should not exceed 1.8 mSv/y.

2.2.2.3. National regulations

Recently, several countries have evaluated their regulations regarding radioactive effluent releases from nuclear installations. This section will presents some national regulation in different countries.

2.2.2.3.1. *China*

The Law on the Prevention and Control of Radiation Pollution of the People's Republic of China has went into effect on October 1, 2003. The purpose of this law is to prevent and control radioactive pollution, protect the environment, ensure human health, and promote the development and peaceful use of nuclear energy and technology. The law establishes pollution and control measures for "radioactive pollution discharged in the course of site selection, construction, operation, and decommissioning of nuclear installations and in the cause of development and utilization of nuclear, technology, uranium (thorium) and accompanying radioactive mines in the territory of the People's Republic of China and in the territorial waters under its jurisdiction." Article 3 presents an important aspect of this law as it stipulates that, when concerning the prevention and control of radioactive pollution, the State should apply the principles of putting prevention first, combine prevention and control measures, exercise rigorous control, and give priority to safety.[83]

2.2.2.3.2. *Belgium*

The general regulation for protection of the population, workers, and the environment against the risk of ionizing radiation (Royal Decree of 20.07.2001) includes provisions limiting the exposure of the public to 1 mSv/y.

2.2.2.3.3. *France*

Decree 95-540 of May 4, 1995, and an Order dated November 26, 1999, set out technical directions concerning the discharge limits and method of sampling from discharges released by "Basic Nuclear Installations (BNI)"; the creation of these installations and their discharges both being subject to specific authorization.

2.2.2.3.4. *Japan*

The national standards of radiation protection for a nuclear installation are provided in the Law for the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors, the Electricity Utilities Industry Law, etc. and related government ordinances, ministerial orders, and notifications based on these laws and guidelines. The recommendations of the ICRP are given due consideration and are incorporated into national legislation and regulations. The ICRP 1990 recommendation on radiation protection was incorporated into them in April 2001, after revision of related ministerial orders and notifications.

2.2.2.3.5. *United States*

Nuclear Regulatory Commission (NRC), under the Code of Federal Regulations (CFR), established revised requirements to its standards for protection again radiation.[84] NRC stated that:

> Due to the practice of maintaining radiation exposures ALARA ("as low as reasonably achievable"), the average radiation dose to occupationally exposed individuals [was] well below the limits in either the previous or amended 10 CFR Part 20 and also below the limits recommended by the ICRP.

In addition, NRC stated that:

> Until the final ICRP recommendations are published, and the need for further revisions in NRC regulations established, the Commission believes it would be advisable to proceed with the promulgation of the proposed dose limits [of 5 mSv per year], rather than deferring the dose reductions that are already associated with [its] amendments to Part 20.

As a result of the application of the ALARA philosophy to effluent release standards in Appendix I to 10 CFR Part 50 for nuclear power reactors and the U.S. Environmental Protection Agency's (EPA's) 40 CFR Part 190 for the uranium fuel cycle, dose from radioactive effluents from the fuel cycle were already much less than 1 mSv per year standard in the final rule. The 1 mSv per year remains as the level recommended by the ICRP in 1985 as the principle dose limit for members of the general public. More recently, in 1996, 10 CFR 20.1101 required an additional ALARA value for air emissions from licensed facilities that require that the individual member of the public likely to receive the highest dose will not receive in excess of 0.1 mSv per year from air emission. Failure to meet this requirement requires the licensee to submit a written report to the regulatory authority (NRC or the Agreement State). This change in regulation eliminated dual regulation of air emissions that had been previously regulated by both NRC and EPA.

2.3. *Risk Informed Regulatory Process and Importance Measure*

The fundamental objective of all nuclear safety regulatory bodies is to ensure that nuclear facilities are operated in an acceptably safe manner. Regulatory body should strive to ensure that its regulatory decisions are technically sound, consistent from case to case, and timely. The basic elements of regulatory decision-making process include clear definition of the issue, assessment of the safety significance, determination of laws, regulations or criteria to be applied, collection of relevant information and data, judgment the expertise and the resources needed, agreement on the analyses to be performed, assigning priority to the issue among the other workload of the agency, making a well-informed decision, and finally write a clear decision and its basis and publish the decision when needed.

2.3.1. *Using Risk Information in Regulatory Decisions*

Most of the safety regulations were established before the development of probabilistic safety analysis methods. These regulations were developed using engineering judgment and analyses to specify rules about design features, operations, and quality assurance. This deterministic approach, using conservative assumptions in analyses and supplemented by following the defense in depth safety philosophy, has generally resulted in substantial safety margins that have served the interests of safety well over the years.

To some extent, safety regulations have always been risk informed, in the sense that there was an attempt from the earliest times to design a plant's safety systems and accident mitigation systems with capabilities commensurate with the risk significance of design basis accidents thought to pose the most risk to public health and safety. These qualitative risk insights were sometimes augmented by quantitative risk analyses.

Since the introduction of a complete probabilistic safety assessment (PSA) framework in 1975, PSA methodology has matured and found widespread usage in different countries. By now, there is a vast literature on the technology and uses of PSA, and it is generally accepted among different regulatory bodies that PSA methods can be used to augment the traditional deterministic methods for regulatory decision making. In many cases, PSA provides deeper insights and a more balanced picture of the actual risks posed by operation of nuclear plants than the largely conservative deterministic analyses. At the same time, it is recognized that a PSA, like all other methodologies, has limitations in portraying the total risk at a plant. For example, a PSA cannot model safety culture and is, therefore, unable to quantify the risk impact of a poor safety culture at the plant. For this reason, regulators are generally cautious in using PSA bottom line estimates of risk (such as core damage frequency) as the sole basis for making regulatory safety decisions for a plant. However, a PSA does not have to be perfect to be of value to the regulator and the operator. Furthermore, many of the concepts in PSA need modification when the risks of waste disposal are considered, since the regulatory concepts for disposal require projecting doses many generations into the future.[85] Therefore, recognizing the strengths and weaknesses of probabilistic safety analyses, the regulator is faced with the question of how extensively to use risk information in its regulatory decision-making process.

In some countries, the regulatory body has the explicit policy to use PSA wherever practical in its decision-making process as a complement to deterministic approaches. Other regulatory bodies rely largely on deterministic regulations and methods, with only a limited use of PSA information. Some of the areas where it is generally agreed that PSA can be most useful in identifying plant vulnerabilities, ranking accident sequences according to their relative contribution to risk, ranking relative risk importance of different systems, components, and operator actions, specifying equipment allowed outage times and surveillance intervals, scheduling maintenance and outage activities, and analyzing operating events for lessons learned.

In the final analysis, there is no single approach to use risk information in decision making that is correct for all regulatory bodies. Each regulator must judge for itself how much weight should be given to risk information and at what pace to introduce risk-informed judgments into its decision-making process.

2.3.2. *Importance Measure*

The quantitative data that can be calculated from a PSA to characterize a particular phenomenon or problem, which relates to the risk or safety of a nuclear power plant, could be divided into global measure and importance measure. Global factors are used to characterize risk directly, while importance measures are used to characterize the contribution to the risk of the different basic events modeled in a PSA or the role they play in the defenses against those risks.

2.3.2.1. Global factors

A general definition of risk (or quantity or risk parameter) metrics is given that can be assessed at different levels of detail in the power plant, including the global, overall level integrating the effects of accident sequences on the public and the environment. Four successive levels of details are defined[86]:

1. Systems and components levels: including the unavailability of components, systems, safety functions, and frequency of preventable maintenance-related failures.
2. Plant level: including frequency of emergency shutdowns, significant events (i.e. core damage precursors), and core damage frequency (CDF).
3. External release: including frequency of containment failure or conditional probability of failure and large early release frequency (LERF).
4. Damage to public and social domains: including risk of individual deaths and total dose received by the population.

The global factors mainly used in applications are as core damage frequency, large early release frequency, and conditional core damage probability.

2.3.2.2. Importance factors

These factors (or importance measures) most referred to are the three conventional factors: risk reduction worth (RRW); absolute or relative risk achievement worth (RAWa or RAW), which is characteristic of the contribution to defense-in-depth; and absolute or relative Fussell–Vesely factor (FVa, FV) and Brinbaum importance (BI). Table 3 lists these measures and their definition.[87]

Table 3. Importance Measure and Their Definition.

Risk Importance Measure	Principle
Risk reduction (RR)	$\mathrm{R(base)} - \mathrm{R}(\mathrm{x_i} = 0)$
Fussell–Vesely (FV)	$\frac{\mathrm{RR}}{\mathrm{R(base)}}$
Risk reduction worth (RRW)	$\frac{\mathrm{R(base)}}{\mathrm{R}(x_i=0)}$
Risk achievement (RA)	$\mathrm{R}(x_i = 1 - \mathrm{R(base)}$
Risk achievement worth (RAW)	$\frac{\mathrm{R}(x_i=1)}{\mathrm{R(base)}}$
Criticality importance (CR)	$\frac{\mathrm{RA} \times x_i\mathrm{(base)}}{\mathrm{R(base)}}$
Partial derivative (PD)	$\frac{\mathrm{R}(x_i+\partial x_i)-\mathrm{R}(x_i)}{\partial x_i}$
Brinbaum importance (BI)	$\mathrm{R}(x_i = 1) - \mathrm{R}(x_i = 0)$

Van der Borst[87] concluded that from maintenance and operation optimization applications, a combination of RAW and FV importance should be used. In applications where ranking is important, only one importance measure is needed. To identify potential components to improve the safety, the Fussell–Vesely factor alone could be used. To identify the potential components for T&M relaxation, Brinbaum importance alone could be used.

2.4. *Technical Methods to Control Radioactive Contamination*

2.4.1. *Remediation of Contaminated Sites*

The nature of radioactive contaminants makes them unique when compared to other contaminants. First, their radioactivity (i.e. radiation hazards) means that they may be considered a risk sometimes at concentrations lower than toxic elements (e.g. arsenic or heavy metals). However, unlike these elements, radioactive contaminants are subject to radioactive decay, meaning that the impact or potential threat of the contaminant is reduced with time. The time scale over which this will occur depends on the half-life of the contaminant. Since half-lives vary from seconds to millions of years, the extent to which decay that assists remediation operations depends strictly on the contaminant(s). However, unlike organic contaminants, the decay of radioactive contaminants cannot be influenced by the remediation technology. These decay properties impact upon the efficacy of any particular remediation operation and will be central to the selection of any technology option. IAEA defined criteria to support the remediation program decision-making process. These criteria are based on the definition of six bands for possible remediation situation each cover an order of magnitude in dose or risk.[88] Band 1, including annual doses less than $10\,\mu$Sv above background, represents risks that would be regarded as insignificant in the majority of situations. Criteria for risk insignificance have been determined based on the exemption and clearance level.[89] Band 2 represents annual doses in the range of tens of μSv above background; this range represents acceptable public exposure as a result of a set of planned actions, i.e., a justified practice.[88] Band 3 represents risks that might be considered reasonable as additional risks from a justified practice, provided that they were as low as reasonably achievable; this band includes annual doses in the range of hundred and some hundreds of μSv.[90,91] Band 4 represents risks corresponding to doses of the order of a few mSv/a. These doses are not considered acceptable. Band 5 (doses of tens of mSv/a) represents risks that would generally be regarded as unacceptable from any source (with the exception of necessary medical treatment). Band 6 (doses of hundreds of mSv/a or more) represents risks in terms of serious deterministic effects or a high probability of stochastic effects, which are clearly insignificant. Table 4 illustrates the IAEA criteria for the beginning of remediation program for contaminated area.[88]

Table 4. IAEA Criteria for Beginning of Remediation Program.[91]

Band	Need for Remediation Actions	Acceptability of Release	Range of Annual Doses
6	Remediation or prevent use	Not suitable for release	>100 mSv/a
5	Remediation or restrict use	Not suitable for release	10–100 mSv/a
4	Remediation decisions based on justification/optimization	Release may be possible subject to regular review of situation	1–10 mSv/a
3	Remediation unlikely unless constrained	Release possible situation may need occasional review	0.1–1 mSv/a
2	Remediation unlikely to be necessary based on radiological risks	Release likely review only if a problem becomes apparent	10–100 μSv/a
1	No remediation necessary	Can be released without controls	<10 μSv/a

A number of different nontechnical and technical factors directly impact the decision-making process of the remediation program. The nontechnical factors include economic factors, public perception/acceptance and public participation, costs, funding, and the availability of resources. The weight of these factors varies from case to case and can be driven by a variety of considerations, including technological, economic, and sociopsychological situations.

Economic and social implications that affect the remediation decisions depend on the size of the contamination problem. Those implications may occur over short- or long-time-scales. Decisions are often taken based on political grounds and not necessarily related to scientific or technical aspects of the environmental contamination problem. On the other hand, since the remediation programs are financed from public money the economic benefits, or detriments for that matter, of decisions on remediation projects need to be evaluated *a priori*.[92] Table 5 illustrates a simplified tabular method for measuring the performance and societal impact of a remediation option.[93] Environmental remediation cost is also an important factor that influences the decision of initiating a remediation program and the choice of technical option. Table 6 represents the cost estimate of a remediation program for uranium-contaminated soil and associated disposal.[94]

Technical factors include the assessment of the ability of the technology to reduce risk to the health and safety of the public and to the environment, the reliability and maintenance requirements for the technology, the infrastructure available to support the technology, the ease of accessing the technology and associated services, the risk to workers and public safety during the implementation of the technology, the environmental impacts of the technology, the ability of the technology to meet regulatory acceptance, and the obtaining of community acceptance. The

Table 5. Societal and Infrastructure Impacts.[93]

Impact Level	Societal Impacts in the Contaminated Area
1	No social or economic disruptions occur; no commercial, residential, or agricultural displacement occurs; and no adverse impacts on water resources occur.
2	In-migrating population of about 10% of the resident persons is dispersed within an area; no major social disruptions result; disruption of existing business patterns is avoided by standard economic planning measures; no adverse impacts on water resources occur, but minimal commercial, residential, or agricultural displacement results.
3	In-migrating population of approximately 10% of the resident persons is concentrated within a few communities; major upgrading of the public infrastructure is required; 25% of residents have lifestyles and values that are unlikely to match those of in-migrants; major social disruptions do not result; disruption of existing business patterns is avoided by standard economic planning measures; minor diversion of water resources from other activities occurs; half of the land is privately owned, and commercial, residential, or agricultural displacement results.
4	In-migrating population of approximately 20% of the resident population is concentrated within a few communities; major upgrading of the public infrastructure is required; affected communities have homogenous lifestyles and values that do not match those of the in-migrants; significant disruption to the existing business patterns and substantial economic decline during or after completion occurs; major diversion of area water sources occurs, resulting in impacts on development in the affected area; all land is privately owned, and commercial, residential, or agricultural displacement results.
5	Changes in the level of availability of public infrastructure include schools; police and fire services; water, sewer, and solid-waste systems; and recreation facilities.

Table 6. Remediation of Uranium-contaminated Soil and Associated Disposal Cost Estimate.[94]

	Cost Element	Unit Cost (US$/m^3)
Conventional disposal costs	Excavation/screening	130
	Transportation	390
	Stabilization/solidification	260
	Disposal	293
	Total unit costs	1,073
Disposal costs using segmented gate system and containerized vat leaching techniques	Excavation	130
	Soil processing via SGS	78
	Well chemistry	325
	Disposal and transport	293
	Total unit costs	826

Table 7. IAEA Technology Evaluation Matrix.[95]

Evaluation Factor	Exemplary	Acceptable	Unacceptable
Performance	Near 100% removal	Removes contaminants to desired limit	Mobilized or additional contaminant
Reliability	Near 100% reliable	Available without excessive down time	Unreliable
Maintenance	Minimal	Occasional	Unavailable suppliers or at great cost
Cost	Costs recoverable against credits	Cost within acceptable levels	Excessive cost
Infrastructure support technology	Not needed or fully available and already in place	Available	Unavailable or requires significant expense to provide
Availability	Well proven	Demonstrated and available in short time frame	Unproven/early in development
Risk	No risk to public or operators	Risk to public or operators within regulatory guidelines	More risk than if nothing done
Impact on environment	Clean and green	Little effect on overall ecosystem	Significant pollution/damage
Regulatory acceptance	Exceeds regulatory standards	Meets regulatory standards	Fails regulatory standards
Community acceptance	Wholehearted acceptance without reservation	Acceptance with two-way dialog	Unacceptable

above-mentioned technical factors should be integrated in a structured approach to assess the decision-making process to select appropriate technologies. Table 7 lists a technology evaluation matrix developed by the IAEA; this matrix provides a subjective ranking scale for each factor. The scale offers three categories, which can be classified as exemplary, acceptable, and unacceptable. A technology assigned as unacceptable would be disqualified from further consideration.[95]

There are many ways to classify remediation technologies, but generally they could be classified according to their application either *in-situ* or *ex-situ*. *In-situ* remediation takes place within the soil/rock/water media, whereas *ex-situ* techniques rely on the removal of the contaminated materials (e.g. groundwater) prior to treatment. Both of these categories can be further subdivided into physical, chemical, biological, and thermal techniques. The applicability of these options to the remediation of radioactive contaminated sites are presented in Table 8 (a and b).[96,97] To support the remediation decision-making process, IAEA proposed a phased approach

Table 8(a). The Applicability of Different *In-situ* Remediation Technology to the Radioactive Contaminated Sites.[96]

Category	*In situ* Technique	Type of Application
Physical	Electro remediation, capping, barrier, hydraulic containment	Maybe suitable either in conjunction with the techniques, and/or following detailed consideration of site-specific characteristics
	Detector-based segregation	Commonly used, well-developed technology, and effective
	Soil vapor/dual phase extraction	Not applicable
Chemical	Soil flushing by chemical leaching, and surface amendment	Maybe suitable either in conjunction with the techniques and/or following detailed consideration of site-specific characteristics
	Stabilization/solidification	Commonly used, well-developed technology, and effective
Biological	Phytoremediation and monitored natural attenuation	Maybe suitable either in conjunction with the techniques and/or following detailed consideration of site-specific characteristics
	Bioremediation	Not applicable
Thermal	Vitrification	Not applicable

Table 8(b). The Applicability of Different *Ex-situ* Remediation Technology to the Radioactive Contaminated Sites.[96]

Category	*In situ* Technique	Type of Application
Physical	Electroremediation	Maybe suitable either in conjunction with the techniques and/or following detailed consideration of site-specific characteristics
	Excavation and disposal	Commonly used, well-developed technology, and effective
	Soil washing	Experimental or pilot scale
	Soil vapor extraction	Not applicable
Chemical	Soil washing by chemical treatment	Experimental or pilot scale
	Chemical treatment, solidification/stabilization, and surface amendment	Maybe suitable either in conjunction with the techniques and/or following detailed consideration of site specific characteristics
Biological	Bioremediation	Not applicable
Thermal	Vitrification	Experimental or pilot scale
	Incineration/thermal desorption	Not applicable

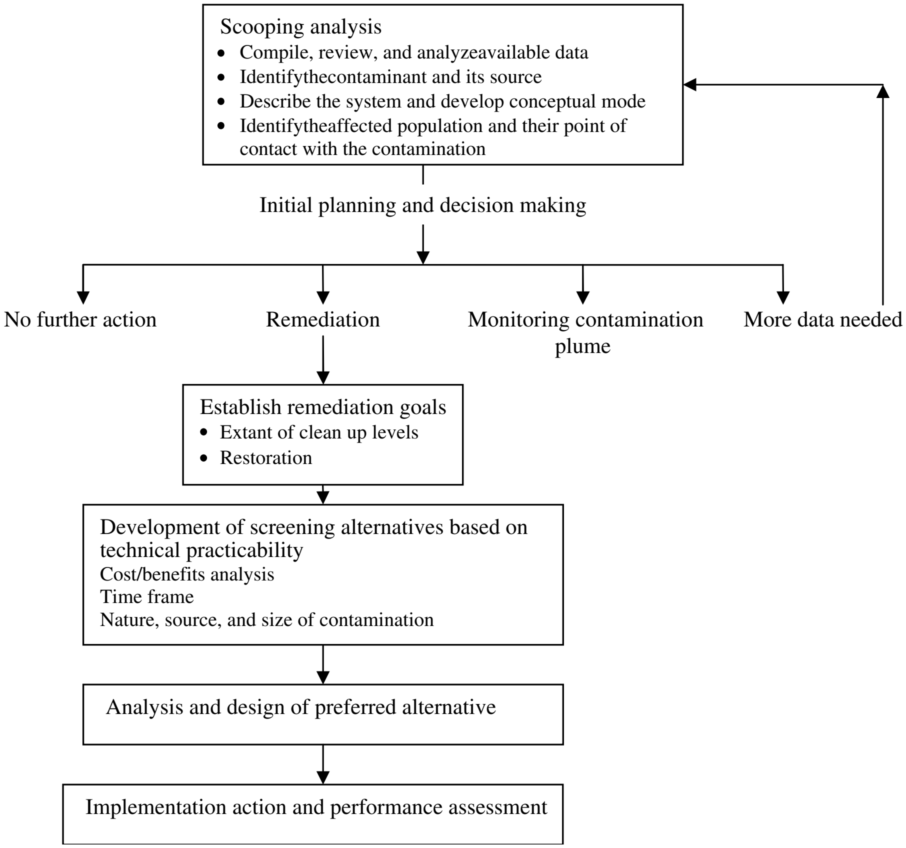


Figure 10. Phase Procedure for Support the Decision Maker.

(Fig. 10).[98] This allows for a cost-effective and governmentally sound disposition of contaminated sites.

2.4.2. *Decontamination*

Decontamination is defined as the removal of contamination from the surfaces of facilities or equipment by washing, heating, chemical or electrochemical action, mechanical cleaning, or alternative techniques.[98–100] The selection of a proper decontamination technique is not a straightforward process; it must be based on several selection criteria that include decontamination effectiveness, and impact of the decontamination technique and its associated constrains.[101]

The requirements for effective decontamination include loose debris removal, adherent particle removal, particle removal from crevices, effect of internal components, production rate, remote operation, and degree of development.[102]

- Removal of loose debris includes the removal of both the loose particles, which have deposited at the bottom portions of the contaminated system in low spots and dead volume spaces, and the loosely adherent and smearable materials that may be attached to the internal surfaces of the system.
- Removal of adherent particles includes the radioactive material that adheres tightly to a surface; more tightly than the smearable film discussed in the first requirement. It also includes corrosion layers if that layer contains radioactive material.
- Particle removal from crevices, evaluate the removal of radioactive particles that migrated into crevices such as valves, demineralizers, pumps, and tanks with internal parts can contain narrow spaces, such as cracks or crevices.
- Effect of internal components used to determine the effect of the internal components in the contaminated equipments on the applicability and effectiveness of a particular decontamination technique.
- Production rate at which a particular method will effectively decontaminate a component is an important requirement in the determination of the effectiveness of the technology, because it is significant to both cost and radiation exposure. However, since production rate is not as important as the effective removal of contaminated material, the weighting factor given to production rate is not usually so high than that assigned to the other requirements.
- Remote operation; ALARA requirement for minimum exposure to operating personnel is one of the more important considerations in selecting a decontamination method. This requirement can greatly reduce the applicability of some otherwise promising decontamination method. The need to protect personnel from excessive exposure will increase the difficulty of the cleaning operation, add to its cost, and increase the time required. The extent of these difficulties will vary inversely with the degree of remoteness of operation of a given decontamination method.
- Degree of development is defined as the extent that the decontamination technique has been developed for industrial use. The technique may have been developed to the point where it is (1) used routinely and the equipment is essentially "off the shelf" in availability. (2) proven, but is still in the developmental stage, and has been employed only on an experimental basis, or (3) still in the experimental stage, and the equipment required for its application requires development rather than refinement.

In addition to the requirements relating to the effectiveness of the different decontamination techniques, there are other requirements concerned with impacts and constraints associated with use of the techniques that include[102]:

- Radiological safety aspects of a particular technique that can greatly influence its latitude for use.

- Secondary waste generation that must be reduced and properly packaged for storage, transport, and disposal. The radioactive waste that is removed from the contaminated surfaces can be expanded in volume by the decontamination agent during the decontamination process and this will lead to increase the disposal cost.
- Need for disassembly, some of the contaminated equipments would have to be disassembled to some degree to provide access to the interior surfaces. Both the degree of disassembly required and the relative difficulty of disassembly would impact the applicability of a particular decontamination technique.
- Accessibility of the contaminated system component is a very important requirement. Depending upon the decontamination technique, one or more openings may be required to decontaminate the system at hand.
- Size of item: for off-system decontamination, large items might be unsuitable to fit off-system decontamination equipment, e.g., an ultrasonic tank. These items must be sectioned.
- Capital cost: initial cost of the decontamination equipment and supporting systems and the expected life of equipment are important factors in the selection of an appropriate decontamination method.
- Operating cost includes the labor and consumable supplies costs. Labor intensive decontamination technique, and/or one that requires a large amount of expensive material is unfavorable. It should be noted that the operating cost of the radioactive contaminated material can be quite different from the cost of nonradioactive industrial cleaning and this is related to the additional costs associated with personnel shielding and waste disposal.
- The feasibility of recycling the contaminated component or system after decontamination can be affected by a number of different factors, which includes the comparison between the decontamination cost the replacement cost. Another factor is the effect of access or sectioning operations that require excessive repair work. In addition, the amount of the removed metal from the decontaminated surface and the final surface quality, since rough surfaces are much more subject to rapid recontamination.
- The tendency to corrode the surface as a result of the reaction between the decontamination agent and the item being decontaminated, both during the decontamination and as a residual effect later on.
- Inherent safety characteristics of the decontamination technique.

Chemical decontamination is usually carried out by circulating chemical reagents in the contaminated system; they are generally most effective on nonporous surfaces. The choice of decontamination agents is based upon the chemistry of the contaminant, the chemistry of the substrate, and the ability to manage the waste generated during the process. The mechanical decontamination is used on any surface where contamination is limited to near surface material. Alternative decontamination techniques include electropolishing, at which an anodic dissolution technique is used where a controlled amount of material is stripped from the contaminated surface along with the contamination. The process works for any conductive metal, providing protective surface coatings are not present, but the choice of electrolyte is important. The components are decontaminated following removal by immersing them in a bath of fluid. Table 9 lists different decontamination techniques and their

Table 9. Applicability of Decontamination Techniques for Different Materials and Surfaces.

Technique	Material	Application Material
Chemical	Strong mineral acids	Stainless steel, inconel, carbon steel, metals, and metallic oxides
	Acid salts	Metal surfaces
	Organic acid	Metal and plastic surfaces, stainless steel, and carbon steel
	Bases and alkaline salts	Carbon steel
	Complexing agents	Metals
	Bleaching	Organic material from metals
	Detergents, surfactants, and organic solvents	Organic materials from metals, plastics, and concrete
	Foam and chemical gels	Porous and nonporous surfaces
Mechanical,	Flushing with water	Large areas (too large for wiping or scrubbing)
	Dusting/vacuuming wiping/scrubbing	Concrete and other surfaces
	Strippable coating	Large nonporous surfaces and easily accessible
	Steam cleaning	Complex shapes and large surfaces
	Abrasive cleaning	Metal and concrete surfaces and hand tools
	Sponge blasting	Paints, protective coatings, rust, and metal surfaces
	CO_2 blasting	Plastics, ceramics, composites, stainless steel, carbon steel, concrete, and paints
	High-pressure liquid nitrogen blasting	Metals and concrete
	High-pressure and ultra-high-pressure water jets	Inaccessible surfaces structural steel and cell interiors
	Grinding/shaving	Floors and walls
	Scarifying/scabbling	Concrete and steel surfaces planning
	Milling	Large number of similarly shaped items
	Drilling and spalling	Concrete only
	Expansive grout	Thick layers of contaminated concrete
Alternative	Electropolishing	Conductive surfaces
	Ultrasonic cleaning	Small objects with loosely adhering contamination
	Melting	Metal

applications.[103] An overview of the strength, limitation, and costs of different decontamination technologies is shown in Table 10.[104]

3. Control of Radioactive Waste

3.1. *Sources of Radioactive Wastes*

3.1.1. *Types of Radioactive Wastes*

The types of the generated radioactive wastes can be divided into aqueous waste, liquid organic waste, solid waste, wet solid waste, biological waste, and medical waste.[106]

3.1.1.1. Aqueous waste

Aqueous waste is generated during nuclear reactor operations and in other operations involving the application of radioisotopes (e.g. medicine, research, and education). The type of liquid waste produced depends upon the particular operation being conducted and can vary extensively in both chemical and radionuclide contents. Most operations, particularly the larger ones, also produce a variety of radioactive liquid wastes from locations such as showers, laundries, and analytical laboratories and from decontamination services. The specific activity of the waste generated depends upon which radioactive materials are used.

3.1.1.2. Liquid organic waste

Liquid organic waste is generated from medical, industrial, and research centers forms a relatively small volume compared with other radioactive wastes. Typically, this waste includes oils, solvents, scintillation fluids, and miscellaneous biological fluids.

3.1.1.2.1. *Oils*

Radioactive oil waste consists of lubricating oils, hydraulic fluids, and vacuum pump oils. This type of waste generally contains only relatively small quantities of beta/gamma-emitting radionuclides, but may also contain trace quantities of alpha-emitting radionuclides, depending on its origin. This waste generally arises from activities in nuclear research centers; tritium contaminated oils may also arise from various medical and industrial applications. Radioactivity levels for oils may vary widely, depending on the applications they are associated with.

Table 10. Overview of Different Decontamination Technology.[104]

Technology	Strengths	Limitations	Special Considerations	Cost (US$/$m^2$)
Organic acids	Applied to wide range of contaminants. Safer than other chemical techniques.	Requires considerable on-hand chemical knowledge for best application.	Contaminant solubilization requires great care in waste treatment. Danger of mobilization of the contaminant.	10.76
Strong mineral acids	Remove very stubborn deposits. Much operating experience from industrial cleaning.	Great care needed operationally due to safety considerations, as it can destroy substrate.	Primarily used for metal corrosion products.	21.53
Chemical foams and gels.	Increased contact time aids performance. Can reach remote and hidden areas.	May require repeated applications to achieve maximum effectiveness.	Care must be taken when flushing since foams can travel to the areas beyond the reach of liquids.	21.53
Oxidizing and reducing agents.	Disrupts matrix where contaminants hide so small amounts can be very effective.	Must be targeted at appropriate situation. Will not work if redox chemistry is not suitable.	Often used as one step of a multiple-step process.	21.53
Strippable coatings	Produce single solid waste. No airborne contamination and no secondary liquid waste.	The spray gun nozzles clog. From a cost perspective, may be best suited for smaller decontamination activities.	Works for only easily removed (smearable) contaminants.	52.20
Centrifugal shot blasting	Good at removing paint and light coatings from concrete surfaces in open areas.	Escaped shot may pose a hazard to workers. Require air compressor, systems for dust collection, and air filtration.	Can be limited by large size, hence unable to get into corners.	368.66
Concrete grinder	Fast and mobile. Less vibration.	Small size limits utility.	Used in combination with other technologies.	31.43

(*Continued*)

Table 10. (*Continued*)

Technology	Strengths	Limitations	Special Considerations	Cost (US$/m^2)
Concrete shaver	Good for large, flat, and open concrete floors and slabs. Fast and efficient.	Does not maneuver well over obstacles. Good for only concrete floors and slabs.	Attractive alternative to handheld scabblers.	14.21
Concrete spaller	Good for in-depth contamination. Fast.	Requires predrilling of holes. Leaves behind a rough and uneven surface.	Limited commercial availability.	199.35
Dry ice blasting	Very good for contamination on a surface.	Cannot remove deep contamination.	Requires support systems: air compressors, dryers, and filters.	N/A
Dry vacuum cleaning	Readily available. Works well with other physical decontamination technologies.	Good for only loose particles.	Typically used in conjunction with other decontamination technologies.	21.53
Electrohydraulic scabbling	Generates less secondary waste than other technologies using water. Very efficient. Removes deep contamination.	Requires a skilled operator. Generates some secondary liquid wastes.	Works best for horizontal surfaces.	107.64
En-vac robotic wall scabbler	Works on large open spaces, including walls and ceilings. Worker exposure to contaminants is limited: remote operation.	Requires additional attachments to address irregular surfaces, obstacles, and tight.	Remote-controlled aspect allows operation in areas unsafe for humans.	139.35
Grit blasting	Different types of grit and blasting equipment are available for a variety of applications.	Generates large amounts of dust and particulates during operation.	Wide range of grits and abrasives are available for special situations.	Based on En-vac system.
High-pressure water	High-pressure systems are readily available.	Generates a significant secondary waste stream.	Can physically destroy substrate. Best used on sturdy structures.	39.07

(*Continued*)

Table 10. (*Continued*)

Technology	Strengths	Limitations	Special Considerations	Cost (US$/m^2)
Soft media blast cleaning	Removes virtually all of the contamination from the surface.	Generates significant amounts of airborne contamination. Lower productivity.	Applicable to surface decontamination only.	49.51
Steam vacuum cleaning	Easy. Washed surfaces dry quickly. Good for large flat surfaces.	Not good for grease. Poor ergonomic design. Not good for irregular surfaces.	Not recommended for surfaces that can be damaged by steam temperatures.	146.82
Piston scabbler	Remotely operated and available. Good for open, flat, and concrete floors and slabs.	Units are loud. Remote units cannot operate close to wallfloor interfaces.	Remote-controlled aspect allows operation in the areas that are unsafe for humans.	64.58

3.1.1.2.2. *Scintillation liquids*

Scintillation liquids result from radiochemical analyses of low-energy beta emitters, such as ^{3}H and ^{14}C. They typically consist of nonpolar organic solvents such as toluene, xylene, and hexane; however, they may also include biological compounds such as steroids and lipids.

3.1.1.2.3. *Solvents*

Spent solvents may arise from solvent extraction processes. The most commonly used extraction solvent is tributyl phosphate (TBP). TBP is diluted for the extraction process usually with a light saturated hydrocarbon, often dodecane or a mixture of paraffin. A variety of organic decontamination liquids and solvents, such as toluene, carbon tetrachloride, acetone, alcohols, and trichloroethane, arise from various operations.

3.1.1.3. Solid waste

Solid waste can be segregated into two main groups; which are compactable and combustible solid waste and noncompactable and noncombustible solid waste.[107] The largest volume of solid waste is general rubbish, which includes protective clothing, plastic sheets and bags, rubber gloves, mats, shoe covers, paper wipes, rags, towels, metal, and glass.

3.1.1.4. Wet solid waste

Wet solid waste, such as spent radioactive ion exchange resins, precipitation sludges, and evaporator concentrates, is generated by the treatment of aqueous waste streams at nuclear research centers or at centralized waste processing facilities.

3.1.1.4.1. *Spent ion exchange resins*

Ion exchange media can be classified into two basic categories: inorganic ion exchangers (both natural and synthetic) and organic resins (mainly synthetic). Most commercial ion exchangers are synthetic organic resins typically consisting of polystyrene cross-linked with divinylbenzene. Spent organic and inorganic ion exchange media may require different treatment and conditioning options. Although regeneration of spent organic resin is possible, the preferred option is direct conditioning of spent resin, as regeneration results in the production of highly acidic and caustic radioactive liquids, which may be difficult to treat.[108]

3.1.1.4.2. *Precipitation sludge*

The product of treatment of liquid radioactive waste by chemical precipitation and flocculation is a sludge containing most of the radioactivity; this can vary greatly in terms of its chemical and physical characteristics, depending on the specific process used.[109] The chemical composition of the sludge differs from the initial waste owing to the addition of the precipitating chemicals.

3.1.1.4.3. *Evaporator concentrates*

Evaporator concentrates are produced through an evaporation process by which the volatile and nonvolatile components of a solution or slurry are separated to reduce both the waste volume and the amount of radioactivity in a liquid effluent. Evaporation is most effectively used for radioactive liquids with high concentrations of salts or other impurities. The concentrate or bottoms product can range from 15 wt% solids to a virtually dry powder or cake, depending on the evaporator type and efficiency and on the chemical composition of the waste stream.[110,111]

3.1.1.5. Biological waste

Biological waste arises from biological, research, and teaching/training practices. This waste includes animal carcasses, contaminated body fluids, and animal tissues. The inclusion of materials having a biological origin clearly distinguishes this type of waste from inorganic materials. A primary example of biological waste is the waste from research involving animals. All discharges (e.g. feces, urine, and saliva) from animals used in research involving radioactive materials must be considered to be potentially contaminated. Animal cage containers must be treated as contaminated until monitored and declared free from contamination.

3.1.1.6. Medical waste

Medical waste may be defined as radioactive waste arising from diagnostic, therapeutic, and research applications in medicine. In addition to being contaminated by radioactivity, medical waste, such as biological waste, can have infectious, pathological, and other hazardous properties. In many instances, the potential additional hazard, either from the waste's chemical, biological, or physical properties, is greater than the radiological hazard.[112] The following types of radioactive waste may occur because of the use of radionuclides in medicine:

- Spent radionuclide generators and spent sealed radiation sources;
- Anatomical and biological wastes (e.g. body parts, tissues, organs, fluids, and excreta from patients administered with radionuclides);
- Miscellaneous aqueous and organic liquids and radioactive solutions;
- Miscellaneous solid dry waste (e.g. gloves, paper tissues, and equipment parts); and
- Miscellaneous waste posing a puncture hazard (e.g. needles, broken glass, and nails).

3.2. *Principles and Objective of Managing Radioactive Wastes*

The International Atomic Energy Agency (IAEA) has developed a comprehensive set of principles for the safe management of radioactive wastes. These principles are applicable to all countries and can be applied to all types of radioactive wastes, regardless of its physical and chemical characteristics or origin. They include the protection of human health and the environment, now and in the future without imposing undue burden now or in the future.[113] In addition to the internationally accepted principles, each country has its own policies that define the aims and objective for the regulatory framework; these might includes administrative and operational measures (i.e., control of radioactive waste generation, safety of facilities, and decision-making criteria).[114]

One of the most important radioactive waste management principles is the control of radioactive waste generation. The objective of this principle is to limit the generation and spread of radioactive contamination and to reduce the volume of wastes for storage and disposal, thereby limiting any consequent environmental impact, as well as contaminated material management costs.[103] The main elements of a waste minimization strategy can be grouped into the following four areas:

1. Keep the generation of radioactive waste to the minimum possible or practicable in terms of both its activity and its volume, by appropriate design measures, facility operation, and decommissioning practices. This includes the selection of appropriate technology, the selection and control of construction and operational materials, the recycle and reuse of materials, and the implementation of appropriate procedures.
2. Minimize the spread of radioactivity leading to the creation of radioactive waste as much as possible by containing it to the possible greatest extent.
3. Optimize possibilities for recycle and reuse of valuable components from existing and potential waste streams. Implementation of recycle and reuse options requires the availability of suitable criteria, measurement methodology, and instrumentation. IAEA proposed a linear decision-tree approach, which could be adopted to evaluate the factors that influence a specific recycle and reuse option, as indicated in Fig. 11.[103]
4. Minimize the amount of radioactive waste that has been created by applying adequate treatment technology.

There are different factors that influence the waste minimization principles such as the technical feasibility and availability of the technology for waste minimization, economic consideration, radiological factors applied to release practice, hazards and risks, national policy, regulatory climate, public acceptance, and legal liability.

International surveys indicate that the applied release practice criteria vary widely among various countries. These criteria might be based on nationally applicable regulations or on a case by case evaluation. Historical examples of clearance criteria from specific projects in various countries are indicated in Table 11.[103] The national regulation in some countries set limits for alpha emitters as three to ten times higher for smaller contaminated areas (hot spots). In some countries, the limits for alpha and beta-gamma are specified separately, while others maintain a specified limits (France, Germany, Sweden, United Kingdom, and the United States). Some of the regulations specifically indicate that decontamination prior to clearance is considered acceptable (Belgium, Germany, and the United States). In Germany, a specific formula has also been applied in some projects/plants to set limit values for those nuclides that can be handled without regulatory control. In addition, further restrictions have been applied in terms of total activity, total mass, and total volume in some of the projects/plants in Belgium, Germany, and Sweden.

3.3. *Elements of Radioactive Waste Management System*

During the establishment of a waste management system, all stages in waste processing are considered, starting from waste generation through sorting and treatment

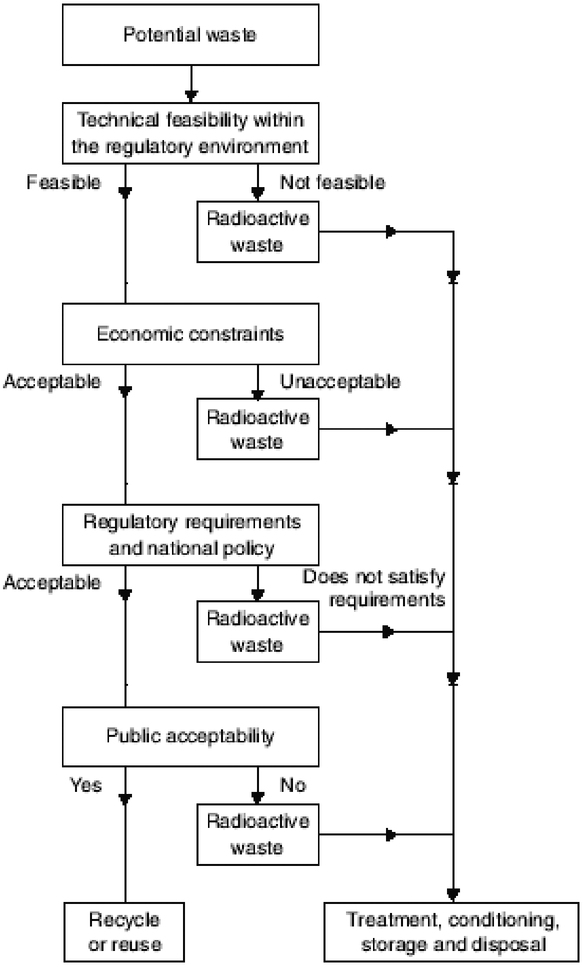


Figure 11. Linear Decision Tree Approach for Recycle and Reuse Applications.[103]

until disposal of these wastes. The basic steps of the radioactive waste management system are depicted in Fig. 12.[115] To achieve the overall goal of safety in waste management, component elements should be complementary and compatible with each other. The core of the waste management system is the technologies that are applied to the waste from its generation to its disposal.

3.3.1. *Transportation*

Safety in the transport of radioactive material is provided through meeting the provisions of transport regulations, which aim to protect persons, property, and the environment from the effects of radiation during the transport of these materials. The transport regulations include requirements on the waste package that ensure

Table 11. Examples of Surface Contamination Limits for Beta–Gamma Emitters Applied in Specific Projects for Unrestricted Reuse or Unrestricted Disposal.[103]

Country	Surface Contamination (Bq/cm^2)	Additional Information Limit
Germany	0.37	Averaged over 100 cm^2 for fixed and removable contaminations and for each single item. Applied to scrap metal originating from nuclear installations.
	0.50	Applied to scrap metal and concrete originating from nuclear installations.
Slovakia	0.37	Case-by-case decision on materials from decommissioning, 100% direct surface measurements.
Finland	0.40	Removable surface contamination over 0.1 m^2 for accessible surfaces. Applied to radioactive substances originating from application in nuclear energy production.
Belgium	0.40	Mean value for removable surface contamination over 300 cm^2, for beta–gamma emitters and alpha emitters with low radiotoxicity.
The USA	0.83	Surface contamination above background over no more than 1 m^2, with a maximum of 2.5 Bq/cm^2 above background if the contaminated area does not exceed 100 m^2.
Italy	1.00	Case-by-case decision for a limited amount of material from decommissioning.
Canada	1.00	Averaged over 100 cm^2 for total contamination, 100% survey of all surfaces.
France	3.70	Materials from decommissioning, 100% direct surface measurements.
Sweden	4.00	Mean value for removable surface contamination over 100 m^2, with a maximum of 40 Bq/cm^2 if the contaminated area does not exceed 10 cm^2. Applied to radioactive substances originating from application in nuclear energy production.
India	4.00	Averaged over 100 cm^2 for fixed uranium contamination. Applied to scrap metal originating from refining facilities. The material is considered for free release if the concentration of uranium in the slag is less than 4 ppm.

its survival under accident conditions. Transport plans can be of a general nature or can be submitted on a case-by-case basis. Simplified transport plans may be used for the transport of relatively small quantities of material, as illustrated in Fig. 13.[116]

3.3.2. *Treatment*

Treatment refers to operations that reduce the volume of the generated wastes. There are various volume reduction technologies[116]; the selection of any of these technologies is largely depending on the waste type. The radioactive waste can be

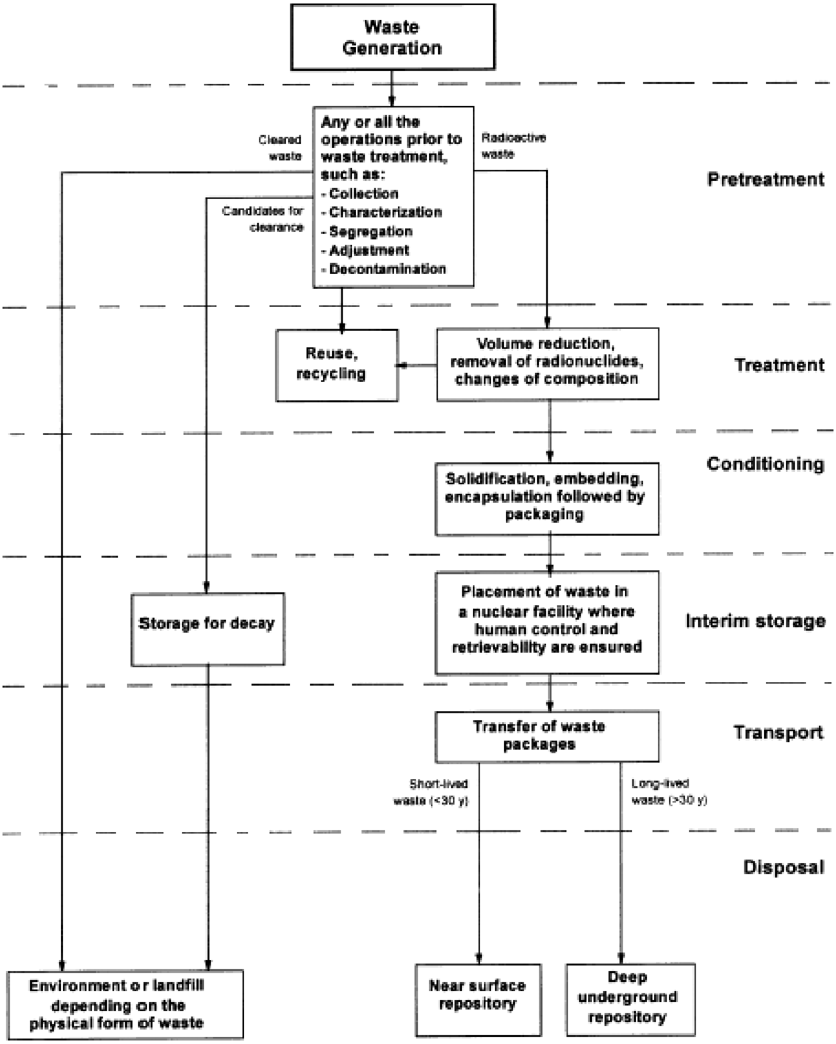


Figure 12. Waste Management Steps.

classified according to its chemical and physical characteristics. Tables 12 and 13 present a general guide showing the main features and limitations of some available aqueous and organic liquid radioactive waste treatment processes.[117] Figure 14 illustrates different decontamination ranges for different treatment options for aqueous liquid radioactive wastes.[118]

3.3.3. *Conditioning*

Conditioning includes operations that produce a waste package suitable for handling, transportation, storage, and disposal.[118,119] The immobilization of radioactive waste

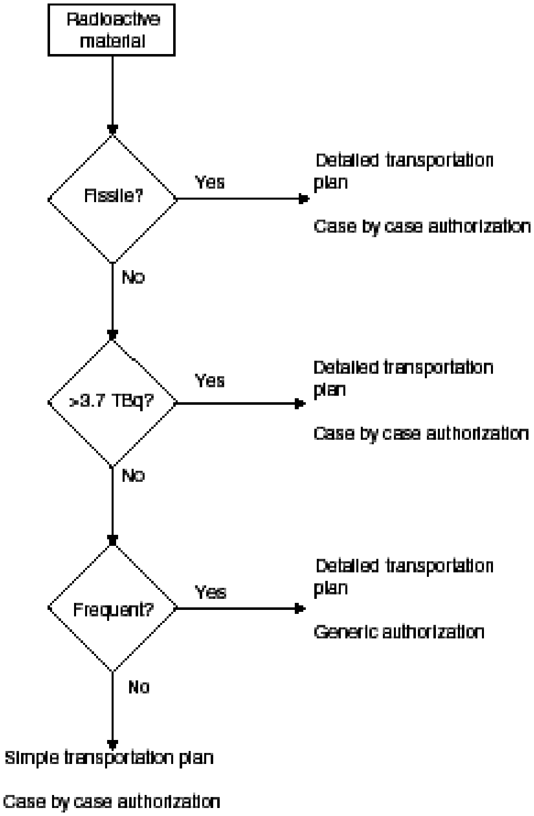


Figure 13. Transport Authorizations Options.[115]

to obtain a stable waste form is an important step to minimize the potential for the migration or dispersion of radionuclides into the environment during storage, handling, transportation, and disposal. When the immobilized waste is packaged, the resulting waste packages must be capable of meeting shielding and containment requirements for handling, storage, transportation, and finally the waste disposal site requirements. The choice of the immobilization waste matrix depends on the physical and chemical nature of the waste and the acceptance criteria for the disposal facility to which the waste will be disposed. Table 14 compares different waste immobilization matrices used in the conditioning of low-level and intermediate-level radioactive wastes.[117]

3.3.4. *Storage*

Storage is an integral part of the waste management system. The main functions of a storage facility are to provide safe custody of the waste packages and to protect both operators and the public from any radiological hazards associated with radioactive

Table 12. Main Features of the Aqueous Waste Treatment Processes.[115]

Treatment Method	Features	Limitations
Chemical precipitation (coagulation/ flocculation/ separation)	Suitable for large volumes and high salt content waste. Easy industrial operations. Not expensive.	Generally lower DF than other processes ($10 < \mathrm{DF} < 10^2$). Efficiency depends on solid–liquid separation step.
Organic ion exchange	DF good on low salt content. Good mechanical strength. Regenerable.	Limited radiation and thermal and chemical stabilities. Resins cost important. Immobilization difficulty.
Inorganic ion exchange	Chemical, thermal, and radiation stabilities better than organic ion exchangers. Relatively easy immobilization. Large choice of products ensuring high selectivity $\mathrm{DF} > 10$–10^4.	Affected by high salt content. Blockage problems. Possible high cost. Regeneration and recycling often difficult.
Evaporation	$\mathrm{DF} > 10^4$–10^6. Well-established technology. High volume reduction factor. Suitable for a large number of radionuclides.	Process limitations (scaling, foaming, corrosion, and volatility of certain radionuclides). High operation and capital costs.
Reverse osmosis	Removes dissolved salts. DF 10^2–10^3. Economical. Established for large scale operations.	High pressure system, limited by osmotic pressure. Non-backwashable, subject to fouling.
Ultrafiltration	Separation of dissolved salts from particulate and colloidal materials. Good chemical and radiation stabilities for inorganic membranes. Pressure <1 MPa.	Fouling-need for chemical cleaning and backflushing. Organic membranes subject to radiation damage.
Microfiltration	Low pressure operation (100–150 kPa). High recovery (99%). Excellent pretreatment stage. Low fouling when air backwash Employed.	Backwash frequency can be high; depends on solid content of waste stream.
Electrochemical	Low energy consumption. Enhances the effectiveness of reactions.	Sensitive to impurities in waste stream. Ionic strength of waste stream can effect performance. Fouling is a problem above 10 g/L total solids.

(*Continued*)

Table 12. (*Continued*)

Treatment Method	Features	Limitations
Solvent extraction	Selectivity enables removal, recovery, or recycle of actinides.	Organic material present in aqueous raffinate. Generates aqueous and organic secondary wastes.

Table 13. Main Features of Liquid Organic Waste Treatment Methods.[115]

Treatment Method	Features	Limitations
Incineration	Decomposes organic nature of waste. High volume reduction. Combined use for other waste. Eliminates infectious hazard.	Secondary waste must be treated. High temperatures are required to ensure complete decomposition. Off-gas filtration and monitoring are required.
Emulsification	Allows embedding of liquid organic waste into cement matrixes.	Low limitations for content of emulsified liquids in the cement matrix.
Absorption	Solidifies and immobilizes organic liquids. Simple and cheap.	Suitable only for small amounts of waste. Absorbed waste may not meet disposal acceptance criteria.
Phase separation (e.g. distillation)	Produce clean solvent. Removes water and detoxifies the waste for direct disposal.	Nonuniversal application. Technology is relatively expensive for this type of waste.
Wet oxidation	Low temperature process. Simpler than incineration. Suitable for biological waste.	Requires storage of oxidizing agent. Residue requires immobilization.

waste. The design of storage facilities must meet national regulatory standards and basic safety principles. Storage facilities are designed to facilitate inspection and monitoring of stored waste, keep exposure to personnel as low as reasonably achievable principle (ALARA), and provide adequate environmental conditions to ensure proper conservation of waste packages during their tenure at the facility. A key function during storage is the maintenance of records allowing the identification of stored waste packages.

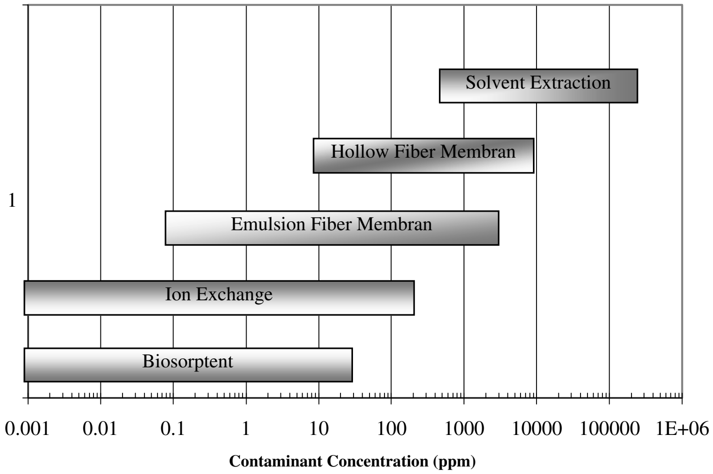


Figure 14. Decontamination Ranges for Different Treatment Technologies (Developed Form Kentish and Stevens, 2001).[116]

Table 14(a). Comparison between Different Immobilization of Process Characteristics.[117]

Process Characteristics	Cement	Polymer	Bitumen
Complexity	Low	High/average	High
Flexibility	High	Average	High
Volume reduction	Negative	Negative	Positive
Cost	Low	High	High

Table 14(b). Comparison between the Applicability of Different Immobilization of Process.[117]

Waste Form	Cement	Polymer	Bitumen
Compatibility with waste streams	Average	Average	High
Waste loading	Average	High	High
Compressive strength	High	Average–high	Low
Impact resistance	High	Average–high	Average
Fire resistance	High	Low–average	Low
Radiation stability	High	Average	Average
Retention of actinides	High	Low	Low
Retention of short-lived	Low	High	High

3.3.5. *Disposal*

The basic objective of disposal is to isolate the waste from water and the human environment under controlled conditions allowing the radioactivity either to decay naturally or to slowly disperse to an acceptable level. The choice of a disposal option depends on the waste type and on local conditions, including geological and hydrogeological conditions, radiological performance requirements, and considerations of sociopolitical acceptance.

3.4. ***Disposal of Radioactive Waste***

3.4.1. *Life Cycle of the Disposal Facility*

The life cycle of any disposal facility comprises different major phases,[121,122] as shown in Fig. 15, covering different types of activities and requiring specific strategies, political decisions, and appropriate human and technical resources. During the lifecycle of the disposal project, there is a need of identifying and assessing the potential nontechnical factors that might impact the disposal project. The greatest impacts generally occur during the construction, operation, and closure phases. The significant of each factor varies from disposal project to another. These factors includes[123]:

- Land resources: Displacement of land resources might result during the excavation of soils, aggregate for road construction, waste cover material, and disposal unit

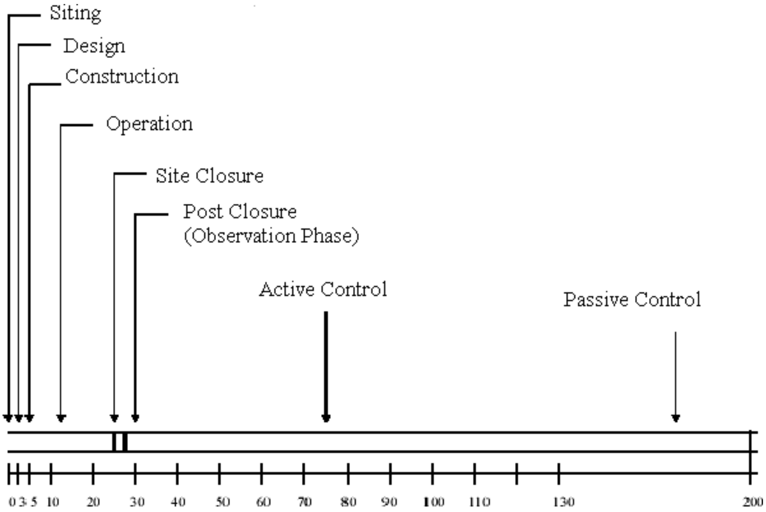


Figure 15. Phases of Disposal Life Cycle.[121]

capping. These disposal materials may be obtained from on-site or off-site sources, resulting in some impact at these sources.

- Ecologically sensitive areas: Areas identified as ecologically sensitive, such as the habitat of rare or protected plant or endangered animal species or special wetlands, may be affected by disposal development, including the potential for erosion of disturbed soils.
- Air quality: Generation and dispersion of dust from increased vehicle traffic and the emission of combustion engine may affect ambient air quality.
- Groundwater resources: Groundwater may be withdrawn to meet the project infrastructure water requirements, potentially including dust control, cement batch plant operation, waste container grouting, drinking water, or septic system or sewers. The withdrawn groundwater may affect well usage, springs, or wetlands in the vicinity of the repository. In addition, the disposal may adversely impact groundwater quality in case of contaminant leakage from the disposal facility.
- Surface water resources: Engineered storm water control features may contribute effluent to surface water bodies or drainage systems and may cause erosion.
- Biotic resources: During the project, a removal of some land area from the baseline plant (flora) and animal (fauna) habitat occurred. This may affect species present on or near the disposal site and along transport routes to the disposal. For wildlife, impacts extend to the home range of movement of the affected species, e.g. feeding and movement territories. In addition, disposal impacts on surface or groundwater resources may in turn affect flora and fauna.
- Visual impacts: The appearance of the natural landscape is likely to be changed by the development of the disposal and related infrastructure construction.
- Historic or archaeological sites: Disposal development, affecting such sites, structures, or artifacts, may alter or destroy historically or archaeologically significant resources, or impair their preservation for future use and enjoyment.
- Demographic: Depending on the size and nature of the project, increases in population may occur in the local community due to incoming workers and family members, especially if the initial size of the host community is relatively small. These changes can affect housing, community social services and infrastructure demands, and community character.
- Social structure: Changes could result if the income levels and educational background of the incoming workers varies significantly from the existing social structure in the local community.
- Community character: During siting, impacts in the local community and adjacent areas may occur based on varying opinions about the proposed disposal. The involvement of interested parties from outside the local community may increase these impacts. Community views may range from perceptions of an undesirable

image and related social tensions to support the economic development and job creation benefits.

- Community health: The nature of the facility to be built may cause anxieties and fears in some individuals and groups that may result in potential human health impacts, especially during the early phases of the disposal development process.
- Employment and labor supply: Disposal development is generally accompanied by local job creation. The total number and the skill levels required will vary depending on project size, nature of wastes accepted, and the technology utilized. New workers may be drawn from the local or surrounding community or the outlying region if the disposal is in an area remote from populated areas. Employment opportunities may be seen as a local benefit. However, the extent of the opportunity depends on the required skill sets. Trade union provisions may also apply. Other local employers may experience a decrease in available skilled workers and perhaps upward pressure on wage levels. Employment needs may fluctuate considerably during different disposal life cycle phases.
- Local economic activity: The project is accompanied by direct purchase of materials, supplies, buildings, vehicles, equipment, fuel, lodging, restaurant meals, professional, and trade services. This purchasing may represent an opportunity for local and regional suppliers and also could result indirectly in new business development. Depending on the level of direct disposal-related spending, these expenditures may have a significant multiplier effect on local and possibly regional economic development. Business development may include complementary nuclear- and engineering-related industries, such as a waste treatment facility, batch cementation plant, or a container fabrication plant.
- Housing: The influx of new employees and their families may place demands on available housing stock, both for rental and ownership, possibly resulting in higher housing costs, increased property values, a shortage of housing, and a potential need to provide additional temporary and permanent housings, depending on the size of the repository. The closure of the facility could result in a surplus of housing stock, which affects housing-market activity. Alternatively, the concern regarding the radioactive waste in the disposal could adversely affect housing-market activity and depress property values. The extent of these impacts may differ considerably during the different disposal phases.
- Education: Depending on the size of the disposal, incoming workers and their families may also put pressure on local educational facilities if there are not sufficient numbers of teachers and classrooms to accommodate new students. Where education provision is the responsibility of the local administrative body, the body may not have the resources to respond the demand for new facilities. During the closure of the disposal, the demand on the educational system will be reduced, possibly resulting in surplus facilities and staff.

- Transportation network: If the shipment of waste to the disposal is by road, this transport will increase traffic levels and possibly road maintenance needs. Construction of new access roads or the improvement of existing roads or the provision of new rail access may be required. Where the local road network is the responsibility of the local administrative body, the body may not have the resources to respond to the potential need for road upgrades or maintenance needs.
- Community services: Depending on the size and nature of the facility, disposal development may produce direct and indirect demands on local community services and facilities, especially if the initial size of the host community is relatively small. These services may include the provision of police and fire protection, hospitals and other health care facilities, social services, emergency response services, and public transportation. Funding for these services may come from a variety of sources. Where community services are the responsibility of the local administrative body, the body may not have the resources to respond to the increasing demands for some of these services. These impacts may arise during the construction, operation, and closure phases.
- Utility availability: The project requires electric power, potentially involving transmission line extension or electricity substation development. Water use and wastewater discharge may require connection to off-site infrastructure, or provision of an on-site water supply well or septic system. Where utility services are the responsibility of the local administrative body, the body may not have the resources to respond to increasing demands. These impacts typically occur during the construction and operation phases, diminish during closure, and are minimal at post-closure, e.g. some provision may be needed for ongoing storm water drainage.
- Park and recreational lands: Lands set aside for parks, hunting, hiking, fishing, or other recreational uses may be affected if disposal development would restrict or prevent future use, or impair the quality of recreational activities. Where park and recreational lands are the responsibility of the local administrative body, the body may not have the resources to respond to increasing demands. These impacts may arise during the construction, operation and, to a lesser degree, closure phases.
- Development plans: Depending on the size and nature of the facility, disposal development may affect the existing land uses and future plans. Concerns regarding the radioactive nature of the waste could adversely affect the future development opportunities. The waste facility itself may not be compatible with current development plans. The ability of the local planning authority to accommodate disposal siting and operation may depend on the size of local and regional communities and on previous experience and attitude toward similar industrial development. After the closure of the repository, the local planning authority may have alternative plans for the future use of the site. These impacts typically occur during the siting, construction, and post-closure phases.

Table 15. Potential Impacts During Disposal Life Cycle Phases.[122]

	Siting	Design	Construction	Operation	Closure	Post-closure
Natural environment						
Land resources			x	x	x	X
Ecologically sensitive areas			x	X		
Air quality			x	x	X	
Groundwater resources			x	x	x	x
Surface water resources			x	x	X	
Biotic resources			x	x	x	x
Visual landscape			x	x	x	x
Historical or archaeological sites	x	x				
Social conditions						
Demographic			x	x	X	
Social structure			x	x	X	
Community character	x	x	x	x	X	
Community health	x	x	x	X		
Economic conditions						
Employment and labor supply			x	x	X	
Local economic activity			x	x	x	
Built environment						
Housing	x		x	x	x	
Education			x	x	x	
Transportation network			x	x	x	
Community services			x	x	x	
Utility availability			x	x	x	
Land use						
Park and recreational lands			x	x	x	
Development plans	x	x			x	

Table 15 summarize these factors and their influence on the disposal project during its different phases.[123]

3.4.1.1. Preoperational phases

These phases cover the period during which a disposal concept is selected and developed in relation to site-specific conditions. The siting process involves close integration between the selection of a suitable site and the development of an adequate disposal design. In recent years, progressively greater emphasis has been placed on meeting social objectives in siting, including acceptance by the local population. These approaches have led to two notable successes in siting new disposal facilities: at Wolsong, Republic of Korea, and at Kincardine, Canada. The objective of the activities in the preoperational phases is licensing of the facility, leading to the construction of the disposal facilities. In this section, the requirements for site selection criteria, disposal design, and waste acceptance criteria will be presented.

3.4.1.1.1. *Site selection criteria*

Guidelines for the selection of a potential disposal site usually include both technical and nontechnical criteria. Typical examples include availability of favorable geology, hydrogeology, and topography; absence of natural resources; avoidance of areas of special cultural or ecological interest; and availability of local infrastructure, including utilities, human resources, transportation routes, and basic physical services.

Candidate sites are assessed based on their ability to contribute to the isolation of the waste and limit radionuclide releases to minimize potential adverse impacts on humans and the environment. Important site characteristics include[122]:

- Geology: The site is expected to possess a stable geology that contributes to the isolation of waste. In addition, the overall predictability of site evolution with regard to its performance in the future needs to be adequate.
- Hydrogeology: The hydrogeological characteristics of the site are expected to limit the contact between waste and groundwater, and thus minimize the mobilization and transport of radionuclides.
- Geochemistry: The geochemical characteristics of the site should be such that the potential for radionuclide migration is minimized. In addition, the chemical conditions should not adversely affect the durability and performance of the waste packages and engineered barriers.
- Seismicity: Seismic events expected to affect the site need to be assessed to ensure that the structures of the facility are designed and built in such a way that their performance will not be compromised.
- Topography: The geomorphological conditions of the site need to be such that surface processes, for example, erosion and flooding, are expected to be minimal in rate and intensity, or absent, precluding, therefore, the possibility that the ability of the site to isolate the waste might be compromised.
- Climate: The climatic conditions of the site need to be such that the isolation barriers can be expected to perform as designed for the required period of time. In addition, possible climatic variations need to be analyzed to ensure that the performance of the isolation system will not be adversely affected.
- Human environment: The implications of human activities in the area need to be considered.

Data collected during site investigation are used as input to the design process and to the associated safety and environmental assessments undertaken to determine site suitability. These data also provide baseline information on the undisturbed characteristics of the site, with which the characteristics of the site in the future can be compared, for example, in the context of confirming the adequacy of the models used to represent the behavior of the repository. Data collection is the most extensive activity to the site investigation process.

The siting process includes four stages, which are (i) conceptual and planning stage, (ii) area survey stage, (iii) site characterization stage, and (iv) site confirmation stage. Public involvement and participation represent one of the most important nontechnical aspects that affect the development of a disposal project. They vary in their nature and extent form country to country, depending on existing legal and political frameworks and on cultural context. Recent experience suggests that broad public acceptance will enhance the likelihood of the disposal approval. An important element in creating public acceptance is the perceived trust and credibility of the responsible organization and of the reviewing agency or agencies. Approaches have been developed to achieve improved credibility by giving the interested public a chance to express their views, by appropriate consideration of public comments, and by providing open access to accurate and understandable information about each phase of the disposal life cycle. The transparency and traceability of the decision-making process are important to generate public trust.[123]

3.4.1.1.2. *Disposal design*

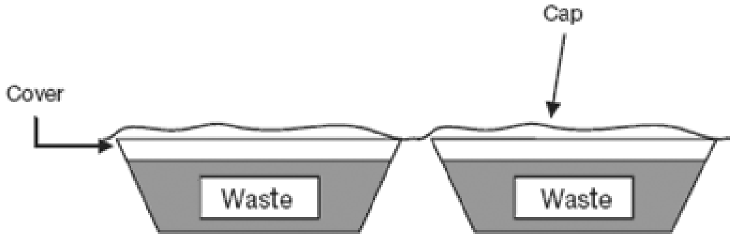
The disposal should be designed to provide adequate isolation of disposed waste for all times in the future. In this regard, adequate isolation means that any releases from the facility must be below health-based limits at any time in the future. Strategies to achieve this goal may be based on the performance of the engineered barriers or on the characteristics of the geological setting. The goal is for the overall disposal system to produce adequate performance, rather than an undue focus on any single part of the system. The design of disposal rely on the multi-barrier concept, in this concept the natural and engineered barriers systems components are used to isolate and retard radionuclide migration into the surrounding environment and to dilute the released radionuclides toward the biosphere.

The period of time for which performance credit can be taken for institutional controls is generally predefined by the regulatory authorities, taking into account the characteristics of the site, the relevant regulatory requirements, and various societal and ethical factors. The quantities and characteristics of the waste that needs disposal are also critical factors for the design of the repository. Based on the characteristics of the disposal site and waste and the anticipated duration of institutional controls, a detailed design of the disposal is developed. The detailed design may include a limitation of the hazardous content of the waste through definition of appropriate waste acceptance criteria. The disposal facility includes the waste emplacement area, buildings, and services for waste receipt. The design and layout of the site varies depending on the type, characteristics, and quantities of waste and on the site characteristics.

Disposal options are categorized as geological and near surface. Near-surface disposal includes two main types of disposal systems: (i) shallow facilities consisting of disposal units located either above (mounds, etc.) or below (trenches, vaults, pits, etc.) the original ground surface and (ii) facilities where the waste is emplaced at greater depths, usually in rock cavities. Geological disposal refers to disposal at greater depths, typically several hundreds of meters below ground. Figure 16 presents various design concepts for radioactive waste disposal.[124–126]

Different shallow disposal designs have been practiced in various countries; these designs could be classified as:

- The covered trench concept is the oldest and simplest of the disposal concepts, which consists of placing waste into excavated trenches and covering the filled trenches with soil. Disposal sites using this concept frequently have retrofitted engineered barriers. This concept has been applied at Drigg disposal facility in the United Kingdom.
- The closed vault concept consists of a concrete vault into which is placed packaged and/or treated waste. The void may be backfilled and the structure closed with concrete slabs, which may be sealed by, for example, asphalt. The whole structure is then protected by an earthen cap. Examples of the application of this concept in Centre de l'Aube in France, El Cabril in Spain, and Rokkasho-mura in Japan.
- The free-draining vault concept in which infiltration is controlled by placing waste in a dry permeable layer and covering the waste with an impermeable concrete



(a)

Figure 16. Disposal Options: (a) Simple Disposal Trench,[124] (b) Shallow Land Disposal Vault,[126] and (c) Geological Disposal,[125] (d) Borehole Disposal.

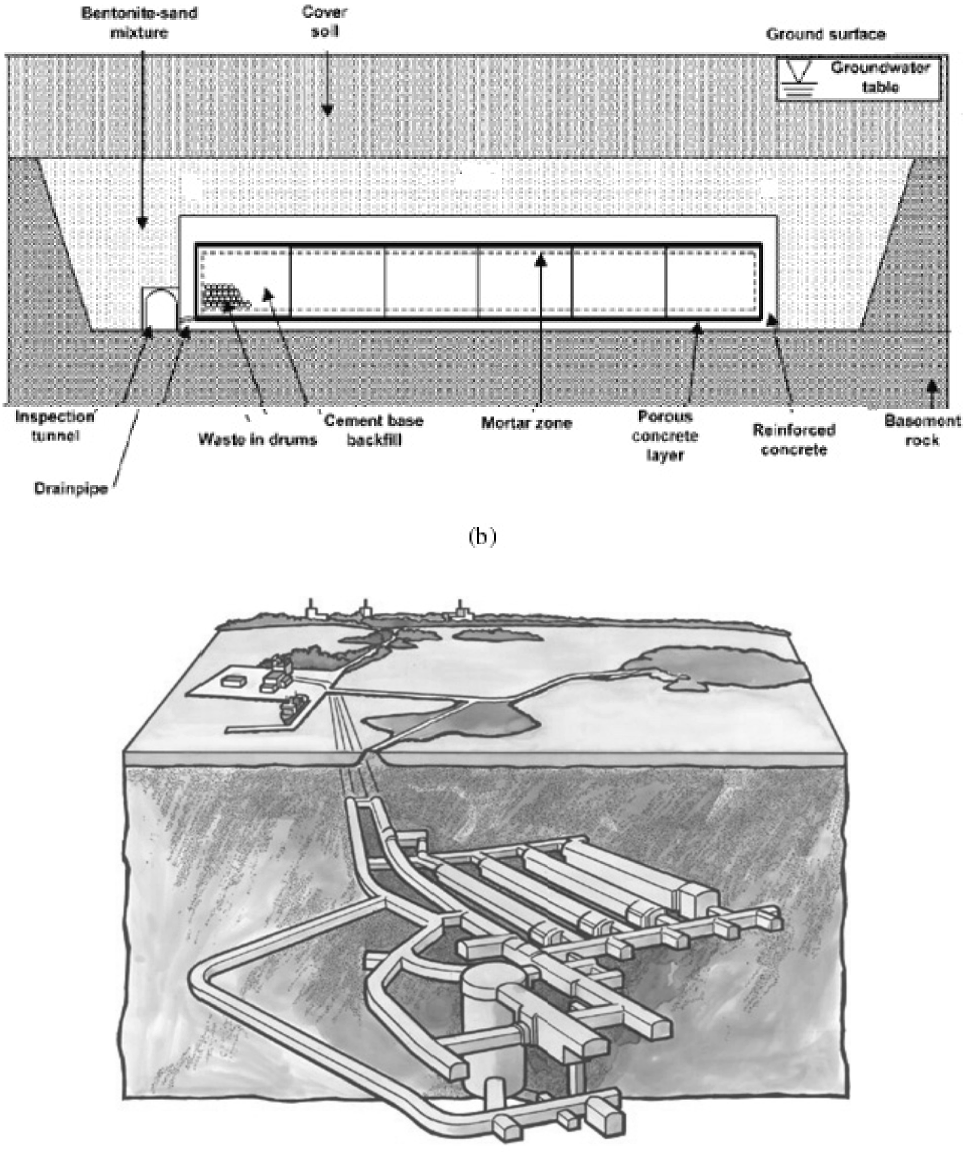
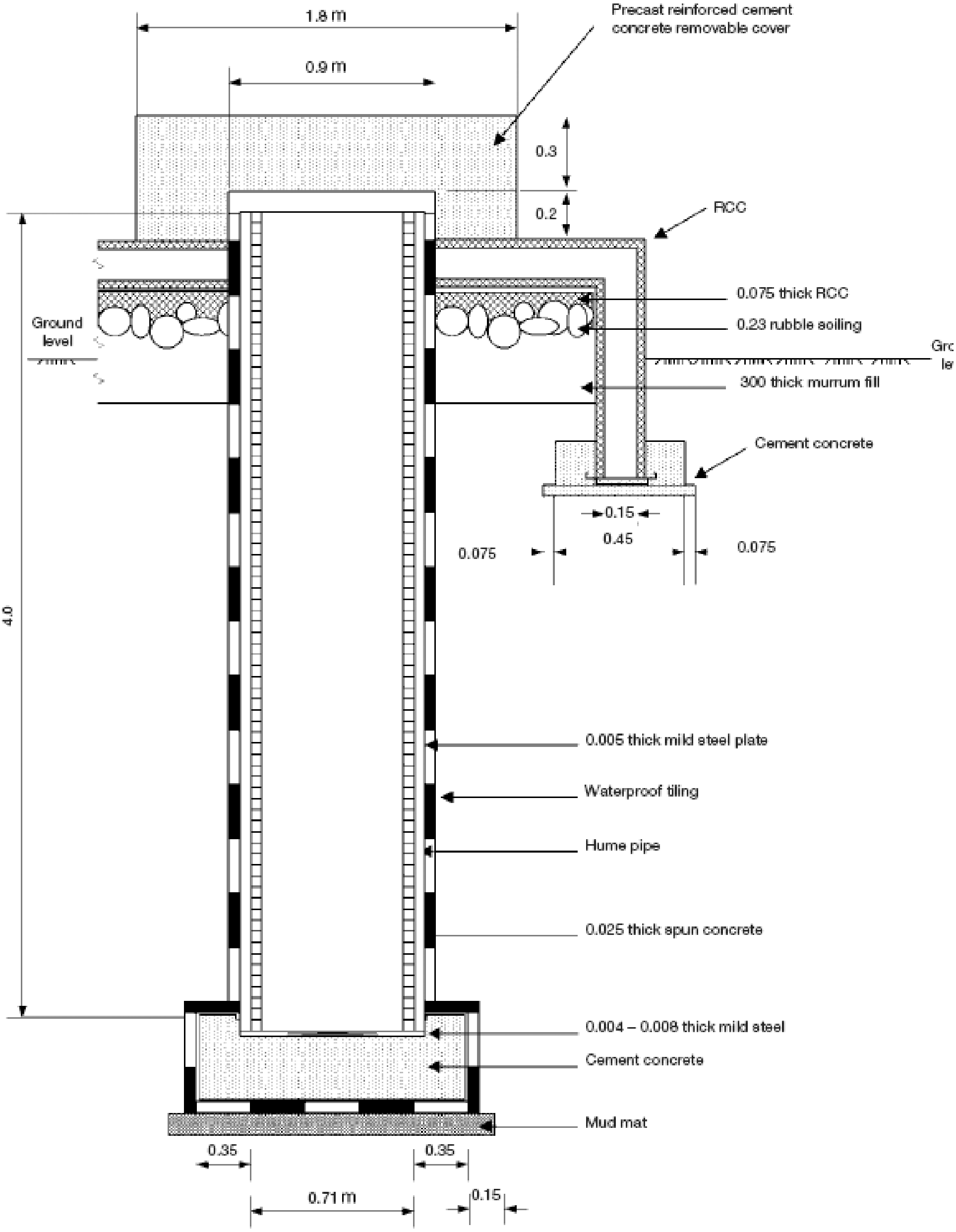


Figure 16. (*Continued*)

roof that is subsequently protected by an earthen cap. This disposal concept has been applied in IRUS disposal facility in Canada.

- The open vault concept has a low-permeability cap that placed over the filled vault without emplacement of a concrete slab. Waste is, however, pretreated to minimize void. The cap is designed to accommodate some settlement.



(d)

Figure 16. (*Continued*)

Facilities built to greater depths include specially excavated caverns tens of meters deep below the Earth's surface, disused mines, natural cavities, and borehole. The borehole disposal concept includes the emplacement of conditioned radioactive waste in a narrow diameter engineered facility operated directly from the surface. Borehole disposal facilities cover a range of design concepts with varying depths and diameters.[127]

Deep disposal, several hundred meters below the surface in stable geological formations, is generally recognized to be an appropriate solution for radioactive waste arising from nuclear power generation, high-level waste from reprocessing operations, spent fuel elements (when considered as waste), and alpha bearing waste.

3.4.1.1.3. *Waste acceptance criteria*

The waste acceptance criteria are predetermined specifications that establish requirements for the waste form and waste packages for disposal in a specific facility,[128] which are established directly by the regulatory authority or by the implementing organization approved by regulatory. These criteria should be derived from consideration of both operational requirements and accidental situation and they should be quantitatively or qualitatively based such that conformance can be either assessed by direct measurement and/or assured by the application of appropriate management methods and controls during the conditioning process.

Compliance with waste acceptance criteria generally requires the definition of a waste package's characteristics and attributes, including performance data (compressive strength, load bearing capability, resistance to impact, corrosion, fire resistance, etc.) and identification of quality-related parameters that need to control to provide assurance of conformance with waste acceptance criteria. In addition, confirmation of the conformance of individual waste packages to the requirements of a waste package specification. Table 16 lists the key waste acceptance criteria that need to be addressed by both the waste package specification and the waste package data sheet.[129]

3.4.1.2. Operational phase

During this phase, the disposal is open and operational. Waste packages, complying with the waste acceptance criteria established during the preoperational phases, are received and placed into disposal units; any auxiliary conditioning/packaging facilities and all supporting units are operating.

At the end of the operational period, appropriate steps are taken to permanently close the disposal. Facility buildings are decommissioned and, if contaminated, may be disposed of in the facility. Closure systems are usually constructed. Appropriate institutional controls are put in place prior to disposal closure. These controls can

Table 16. Identification of Criteria to Be Addressed in Waste Acceptance Criteria.

Waste Acceptance Criteria Item	Waste Package Specification (General Demonstration of Compliance)	Waste Package Data Sheet (Individual Demonstrations of Compliance)
Quality assurance program	A description of the arrangements established by the operator to ensure the effective management and control of all parameters identified as critical to achieve the waste package quality. This description should cover all activities, events, and resources necessary to ensure compliance with these specification.	Certification by those responsible for the operation of conditioning facilities or the conformance of individual waste packages with requirements identified in the waste package specification.
Compliance with statutory and regulatory requirements	Arrangements to ensure compliance with identified statutory and regulatory requirements should be included within the quality assurance program.	
General description of the raw waste — Physical, chemical, and biological properties — Radionuclide content — Fissile content	• A written description of the waste should be provided with the details of its source, volume, and weight. • The characteristics and composition of the raw waste should be identified and where possible quantified with sufficient accuracy. • Limits should be established for those radionuclides and other properties that could adversely affect the suitability of a waste package for disposal where appropriate. • For all components present in the waste, average and limiting values for an individual waste package should be defined along with a maximum limit of fissile content to safeguard against criticalities.	• Confirmation that the raw waste content of a waste package is within the limits defined in the waste package specification should be given. • Where fissile material is present, then it should be confirmed that it is within the permitted fissile mass limit.

(*Continued*)

Table 16. (*Continued*)

Waste Acceptance Criteria Item	Waste Package Specification (General Demonstration of Compliance)	Waste Package Data Sheet (Individual Demonstrations of Compliance)
Description properties weight	• A description of the waste container to be used to hold the conditioned waste should be provided, using drawings where possible, along with details of its mechanical and physical properties. • Reference to a manufacturing specification should be included and the weight of the container empty given.	• Confirmation that the container conforms to the requirements of the manufacturing specification should be given, with reference to a manufacturing release certificate where possible (to provide access to the manufacturing records if necessary) and details of any manufacturing concessions granted.
Details of any immobilizing matrix used including the matrix specification and arrangements for control of quality-related parameters	A description of any matrix used to immobilize the raw waste or elements within it, comprising: — identification of the waste to be immobilized, — details of any pretreatment earned out on the waste, — specification for the immobilizing matrix including its composition ratio rate to immobilized product percentage voidage and degree of homogeneity within the final product compressive strength, — results of tests to assess the acceptability of final product for leaching and release of included radionuclides, and — identification of those parameters where need to be controlled in order that the final product conforms to the specification and a description of the arrangement for monitoring and controlling them.	Confirmation that any immobilizing matrix used meet the requirements of the specification concerned should be given.

(*Continued*)

Table 16. (*Continued*)

Waste Acceptance Criteria Item	Waste Package Specification (General Demonstration of Compliance)	Waste Package Data Sheet (Individual Demonstrations of Compliance)
Package type and variant demonstration of package integrity covering: — Mechanical strength, — Resistance to impact, — Radiation stability, — Fire resistance, — Voidage, — Durability, — Resistance to teaching package identification, labeling, and marking.	• The package type and variant should be defined. • The results of work carried out to assess and demonstrate the integrity of the waste package against each of the identified requirements should be reported. • The system to be used to mark/label packages should be described along with the details of the assignment of a unique identifier (numeric, alphanumeric, or bar code) to each package.	The package type and variant should be recorded on the data sheet. The package identifier should be clearly marked on at least two faces of the container and recorded on the data sheet.
Package weight	• The maximum weight of an individual package should be specified and shown to be compatible with any limit specified in the waste acceptance criteria and/or requirements for the handling of waste packages. • The method of determining this limit should be defined. • Arrangements for determining the weight of each package or verifying that it is within the limit specified should be described.	The weight, surface contamination levels, and dose rate of each package should either be measured or confirmed as being within the limits given in the waste package specification, and recorded on the date sheet on completion of conditioning.

(*Continued*)

Table 16. (*Continued*)

Waste Acceptance Criteria Item	Waste Package Specification (General Demonstration of Compliance)	Waste Package Data Sheet (Individual Demonstrations of Compliance)
Dose rate	• The average and maximum dose rates for an individual package should be specified. • The method of determination should be defined and the specified dose rates shown to be compatible with any limit specified in the waste acceptance criteria and/or handling, storage, and transportation requirements. • Arrangements for determining the dose rate of each package or verifying that they are within the limits specified should be described.	
Storage	Where a package is to be held in interim storage prior to disposal, then a description of the storage facility and the arrangements for monitoring the condition of packages and minimizing any deterioration in their condition should be described.	
Transport	• Arrangements for preparing the package for transport to the repository and demonstrating compliance with national requirements should be described. • Any documentation in addition to the package date sheet required by those regulations should be identified.	Compliance with national (and where necessary international) regulations governing the transport of radioactive materials should be confirmed on the relevant documentation.

(*Continued*)

Table 16. (*Continued*)

Waste Acceptance Criteria Item	Waste Package Specification (General Demonstration of Compliance)	Waste Package Data Sheet (Individual Demonstrations of Compliance)
Consignment documentation	• All documents and records to be handed over to the repository operator when a package is consigned for disposal should be identified and samples attached, where necessary. • Except where the consignment documentation used is that specified in the waste acceptance criteria, it should be shown how the documentation concerned fulfills and meets the requirements of those criteria. • A description of the arrangement for completing this document should be given, along with the details of those personal authorized to sign them.	Completion of consignment documentation as described in the waste package specification.

enhance both the long-term safety of the disposal and public confidence in its long-term performance. Institutional controls may include active controls, such as monitoring, surveillance, and remedial work, and passive controls, such as land use restrictions and record keeping.

3.4.1.3. Post-closure phase

During this phase, following closure of the disposal facility, the site is maintained under institutional control. Access to the site is controlled and a monitoring program, approved by the regulatory body, is implemented. Controlling access to the site is important in that it serves to minimize the potential for human intrusion. During this period, any perturbation of the disposal system revealed by the monitoring and surveillance program can be investigated and appropriate remedial actions can be taken. At the end of the institutional control period, it is expected that the radioactivity in the waste will have decayed to sufficiently low levels that the radiological risk to an inadvertent intruder into the waste is acceptably low. The duration of both the active and passive institutional controls needed to ensure safety depends on many factors, such as the waste characteristics, site characteristics and facility design, and economics. However, institutional controls for near surface disposal facilities are generally considered to be effective up to at most a few hundred years.

3.4.2. *Safety Assessment*

The long-term safety of radioactive disposal must be convincingly demonstrated before its implementation. Assessment of the safety impact arising from the disposal is a main tool to investigate and explain the long-term behavior of a disposal facility. It is the only existing approach for linking observable features of the site with the design goal: the safety of the disposal system in the future.

A summary of the hierarchy of terms commonly used relating to the assessment of the safety impacts arising from the disposal of radioactive waste is given in Table 17. At the top of the hierarchy is the safety case, which uses the results from the safety and performance assessments of the repository linked with other factors that are important for the assurance of safety such as the use of sound science and engineering, QA procedures, safety culture, robustness and defense in depth, and institutional controls.[130,131] At the next level, there are the performance and safety assessments. Performance assessment involves an analysis of the performance of a system or subsystem, followed by comparison of the results with appropriate performance criteria. In contrast, safety assessment is the analysis of the overall system and its impact, followed by comparison with appropriate safety criteria. The performance and safety assessments are, in turn, underpinned by performance and safety analyses. The results of a safety assessment can be presented in a way

Table 17. Hierarchy of Commonly Used Terms Relating to the Assessment of Radioactive Waste Disposal.[130]

<table>
<tr><td colspan="2"><i>Safety case</i></td></tr>
<tr><td colspan="2">It includes performance and safety assessments. In addition, a full line of arguments and evidence that a sufficient set of processes have been analyzed and appropriate models and data used; relevant overall measures of performance and safety are within acceptable ranges, allowing for uncertainties. More qualitative and parallel lines of evidence and reasoning may be also used to support results of the quantitative modeling and to indicate the overall safety of the system.</td></tr>
<tr><td><i>Performance assessment</i></td><td><i>Safety assessment</i></td></tr>
<tr><td>It includes performance analysis. In addition, comparison of intermediate parameters with appropriate criteria set by regulation design targets.</td><td>It includes safety analysis. In addition, testing of arguments that a sufficient subset or of processes have been analyzed, appropriate models and data used, plus comparison of calculated measures of overall performance to regulatory safety limits and targets.</td></tr>
<tr><td><i>Performance analysis</i></td><td><i>Safety analysis</i></td></tr>
<tr><td>Quantitative analysis of some subset of processes relevant to the behavior of the disposal system and calculation of intermediate parameters of interest.</td><td>Quantitative analysis of the set of processes that have been identified as most relevant to the overall performance of the disposal system and calculation of a measure of overall performance relevant within the given national regulatory regime.</td></tr>
</table>

that provides reasonable assurance of the performance of individual system components. Thus, performance assessment can be viewed as an integral part of safety assessment.

There are various assessment methodologies that have been developed to assist in developing an appropriate safety assessment. While there are differences in the detail of the approaches used, safety assessment methodologies have the following key components.[132,133]

- assessment context specification,
- disposal system description,
- scenarios development and justification,
- model formulation and implementation, and
- result analysis of and building of confidence.

Safety assessment of a radioactive waste disposal facility is generally undertaken to provide confidence to government, regulatory authorities, general public, and technical/scientific personnel that the facility will ensure the safety of people and protection of the environment over long timescales. However, this generic objective does not provide a very precise description of what has to be considered in the assessment. The assessment context provides a framework for the performance of the safety assessment, establishing the purpose, the regulatory framework, the assessment end-points, the assessment philosophy, the disposal system characteristics, and the timeframes of concern. The assessment context is intended to provide clear and comprehensive goals for the analysis.

The disposal system is frequently considered to consist of the near field, the geosphere, and the biosphere. The near field includes the waste, and the disposal area, and the engineered barriers of the disposal facility, including the disturbed zone of the natural barriers that surround the disposal facility. The geosphere includes the rock and unconsolidated material that lies between the near field and the biosphere. It can consist of both the unsaturated zone (above the groundwater table) and the saturated zone (below the groundwater table). The biosphere is the physical media at the point of discharge from the geosphere (atmosphere, soil, sediments, and surface waters) and the living organisms (including humans) that interact with them. For the purposes of safety assessment, it is necessary to have a sufficiently clear description of the disposal system that facilitates the development of the safety assessment, ensuring that key features, events, and processes that may affect disposal system safety are adequately described. Since the biosphere is particularly susceptible to the actions of future humanbeings, and since those actions are impossible to predict, assumptions about the biosphere are usually stylized.[5,134]

In a safety assessment of a waste disposal facility, it is important to assess the performance of the disposal system under both present and future conditions, including anticipated and less probable events. Different countries have various requirements for the extent to which low probability events need to be included in the safety assessment. Taking such events and processes into account means that many different factors should be included in the safety assessment and evaluated in a consistent way, often in the absence of quantitative data. This is often achieved through the formulation and analysis of a set of scenarios, which are stylized representations of the potential future conditions that may affect the disposal facility. The scenarios generally need to represent a reasonable set of conditions of concern that may influence the future safety of the facility. However, practical considerations dictate that the number of such scenarios must be limited. The tradeoff between the desire to be comprehensive and the need for limiting the scope of the safety assessment is a primary focus of regulatory reviews of safety assessments.

Once the scenarios have been developed, their consequences in terms of the assessment context are analyzed. Depending on the nature of the scenario, an appropriate approach for its analysis is chosen. For some scenarios, it may be appropriate to use a qualitative assessment approach (e.g. when data are not available). For the scenarios that are to be quantitatively assessed, the scenarios should be organized into a form that can be mathematically represented. A set of model-level assumptions (about dimensionality, boundary conditions, etc.) are needed for each of these scenarios. These assumptions comprise the conceptual model. More than one conceptual model may be consistent with available information for a scenario.

Once the scenarios and associated conceptual and mathematical models have been developed and implemented in software tools, and the associated data collated and implemented, calculations can be undertaken to assess the impacts of disposal facility. The results then need to be collated, analyzed, and presented. The nature of disposal facilities and the requirements for projecting doses long times in the future inevitably leads to uncertainties. To be credible, safety assessments need to provide a sufficient representation of the uncertainties that a skeptical outsider (usually a regulator) can be convinced that the site will be safe. The standard of proof sought in waste disposal safety assessments has been variously called "reasonable assurance" or "reasonable expectation." These terms are invoked to emphasize that absolute assurance is not normally achievable for analyses that project consequences over very long times. Issues of the uncertainties in safety assessments and their special consideration have been discussed in the literature.[18]

Establishing confidence in the disposal development program is an important consideration at all stages of the disposal life cycle. It is particularly important that government, regulatory bodies, public, and technical/scientific personnel should have confidence in the program. A variety of measures can be used to help establishing confidence.[135–138] These include:

- Application of a systematic approach to the disposal program and its associated steps; this approach should have a number of confidence enhancing measures such as measure to insure that each stage of the program and its associated decisions are appropriately and clearly documented; utilization of transparent scientifically and technically justifiable methods, and apply multiple lines of reasoning.
- Peer review of the program as well as of its individual stages; it is an important activity that can be used to achieve scientific and technical confidence in the approaches, methods, data, and decisions made in the development of a disposal facility.
- Demonstration of the robustness of particular aspects of the program; safety assessment have a key role in the demonstration of the site and of the design robustness through the provision of a basis for rational and technically sound decisions relating to their safety. Further confidence can be developed in the design through the use of multiple barriers concept. Additionally, field tests and monitoring are undertaken to demonstrate the appropriate performance of the barriers. Operational monitoring data can be used to confirm that the facility performs according to the design objectives.
- Identification and management of uncertainties; uncertainties arise from the disposal system evolution over the timescales of interest, uncertainty in the

conceptual, mathematical, and computer models used to simulate the behavior of the system and uncertainty in the data and parameters used as inputs in the modeling. In order to build confidence to assist the decision-making process, it is important that these uncertainties are identified and managed appropriately.

- Application of QA procedures throughout the program; an important contribution to building confidence in a repository safety case arises from the application of a QA program.
- Documentation of the disposal program and the preservation and availability of the associated documents are very important to generate confidence in the safety of disposal.
- Involvement of the public in decisions relating to the program.

References

1. Harrison, R.M. (Ed.) (1996). *Pollution: Causes, Effects and Control*, Third Edition, Cambridge: Royal Society of Chemistry.
2. Social trends 28, ONS (1998). Digest of Environmental Statistics Number No. 20.
3. Lamarch, J.R. (1983). *Introduction to Nuclear Engineering*, Second Edition, Addison-Wesley Publishing Company.
4. U.S. Environmental Protection Agency (2007). *Radiation Risks and Realities*, Environmental Protection Agency, EPA-402-K-07-006.
5. ICRP Publication 103 (2008). Recommendations of the ICRP Annals of the ICRP Volume 37/2–4.
6. International Commission on Radiological Protection (1991). *1990 Recommendations of the International Commission on Radiological Protection*, ICRP Publication 60. Annals of the ICRP 21(1–3), Oxford: Pergamon Press.
7. International Commission on Radiological Protection (1990). *Recommendations of the International Commission on Radiological Protection*, ICRP Publication 60. Annals of the ICRP 26, Oxford: Pergamon Press.
8. International Atomic Energy Agency (1996). *International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources*, Safety Series No. 115, Vienna: International Atomic Energy Agency.
9. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (2000). *Report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly*, Annex B.
10. O'Brien, K., Friedberg, W., Sauer, H.H. *et al.* (1996). Atmospheric cosmic rays and solar energetic particles at aircraft altitudes. *Environment International* **22**(Suppl. 1): S9–S44.
11. Khan, H.A. and Haseebullah (1993). Indoor radioactive pollution due to radon and its daughters. *Journal of Islamic Academy of Sciences* **5**(4): 249–255.
12. Li, Y., Schery, S.D., and Turk, B. (1992). Soil as a source of indoor Rn-220. *Health Physics* **62**: 453–457.

13. Pfeiffer, W.C., Penna-Franca, E., Costa Ribeiro, C., *et al.* (1981). Measurements of environmental radiation exposure dose rates at selected sites in Brazil. *Anais Da Academia Brasileira De Ciencias* **53**: 683–691.
14. Veiga, L., Amaral, E., Magalhães, M., *et al.* (1999). Brazilian areas of elevated levels of natural radiation: A critical review and relevant future studies. In: *Second Symposium on Technologically Enhanced Natural Radiation*, Rio de Janeiro, Brazil.
15. Sunta, C.M., David, M., Abani, M.C., *et al.* (1982). Analysis of dosimetry data of high natural radioactivity areas of SW coast of India. In: *Natural Radiation Environment*, K.G. Vohra, U.C. Mishra, K.C. Pillai, *et al.* (Eds.), New Delhi: Wiley Eastern Limited, pp. 35–42.
16. U.S. Environmental Protection Agency http://www.epa.gov/radiation/understand/health_effects.htm, last viewed 10-9-2013.
17. Feinendegen, L.E. (2005). Evidence for beneficial low-level radiation effects and radiation hormesis. *British Journal of Radiology* **78**: 3–7.
18. NCRP Report 152. Report of the National Council on Radiation Protection and Measurements (NCRP) (2005). Performance Assessment of Low-Level Waste Disposal Facilities, U.S. National Council on Radiation Protection and Measurements. Bethesda, MD.
19. Sunta, C.M. (1990). A review of the studies of high background areas of the SW coast of India. In: *Proceedings of the International Conference on High Levels of Natural Radiation*, Vienna: IAEA, pp. 71–86.
20. Cember, H. (1996). *Introduction to Health Physics*, Third Edition, New York: McGraw-Hill.
21. International Atomic Energy Agency (1996). *Environmental Protection: Nuclear Analytical Techniques in Air Pollution Monitoring and Research*, IAEA, Bulletin, 2/1996.
22. Taylor, G.I. (1954). The dispersion of matter in turbulent flow through a pipe. *Proceedings of the Royal Society of London, Series A* **223**: 446–468.
23. Blet, V., Berne, P., Legoupil, S., and Vitart, X. (2000). Radioactive tracing as aid for diagnosing chemical reactors. *Oil & Gas Science and Technology* **55**: 21–71.
24. Blet, V., *et al.* (1997). Application of radioactive tracers for the study of ventilation in industrial premises, paper presented at *1st European Congress on Chemical Engineering*, Florence.
25. International Atomic Energy Agency (1990). *Guidebook on Radioisotope Tracers in Industry*, Technical Reports Series No. 316, Vienna: IAEA.
26. International Atomic Energy Agency (1982). Industrial application of radioisotopes and radiation technology. In: *Procedings of the International Conference on Grenoble*, 1981, Vienna: IAEA.
27. Alan, S.M., Ansari, R., and Khan, M.A. (2001). Application of radioisotopes and radiation in the field of agriculture: Review. *Journal of Biological Sciences* **3**: 82–85.
28. *Isotope Tracers Help Manage Water Resources*, https://www.llnl.gov/str/pdfs/11_97.2.pdf, last viewed 10-9-2013.
29. Ralph M. Kniseley, *What Can Radio Isotopes Do for Man? Medicine and Biology*, http://www.iaea.org/Publications/Magazines/Bulletin/Bull164/16405800211.pdf, last viewed 10-9-2013
30. International Atomic Energy Agency (2004). *Radiotracer Applications in Industry — A Guidebook*, Technical Reports Series No. 423, Vienna: IAEA.

31. Burgress, N.T. (1989). *Quality Assurance of Welded Construction*, Second Edition, Taylor & Francis.
32. International Atomic Energy Agency (1996). *Manual on Gamma Radiography*, Practical Radiation Safety Manual No. 1, Vienna: IAEA.
33. International Atomic Energy Agency (1999). *Radiation Protection and Safety in Industrial Radiography*, Safety Reports Series No. 13, Vienna: IAEA.
34. Loaharanu, P. and Ahmed, M. (1991). Advantages and disadvantages of the use of irradiation for food preservation. *Journal of Agriculture and Environmental Ethics* **4**(1): 14–30.
35. Seligman, H., Gillen, V.A., and Utner, R. (1990). *Insect Control, Isotopes in Everyday Life*, Vienna: IAEA, pp. 15–18.
36. Lindquist, A.W. (1963). *Insect Population Control by the Sterile Insect Technique*, Technical Report Series 21, Report of Panel Vienna October 16–19, 1962, Vienna: IAEA.
37. Farooq, S. and Azam, F. (2002). Molecular markers in plant breeding- III: Practical application and difficulties encountered. *Pakistan Journal of Biological Sciences* **5**(10): 1148–1154.
38. Burk, R.J. (1988). Food Irradiation, Health Physics Society.
39. Codex Alimentarius Commission of FAO and WHO adopted in 1983 a Codex General Standard for Irradiated Foods.
40. Food irradiation, Idaho State University, http://www.physics.isu.edu/radinf/food.htm, last checked 13-09-2013
41. http://www.nrc.gov/reading-rm/doc-collections/nuregs/brochures/br0217/r1/br0217r1.pdf, the regulation and use of radioisotopes in today's world, U.S. Nuclear Regulatory, UREG/BR-0217, last viewed 10-9-2013.
42. International Atomic Energy Agency (1989). *Fission Molybdenum for Medical Use*, IAEA-TECDOC-515, Vienna.
43. Seaborg, G.T. and Wagner, J.H.N. (1996). Nuclear medicine: 100 years in the making, 1896–1996. *American Society of Nuclear Medicine*, p. 20.
44. Gooden, A.W.G. and Stewart, J.S.W. (2008). Long-term results from graded low dose radioactive iodine therapy for thyrotoxicosis. *Clinical Endocrinology* **24**(2): 217–222.
45. International Atomic Energy Agency (1993). Radiopharmaceuticals as therapeutic agents in medical care and treatment, IAEA Bulletin 1/1993.
46. Bly, J.H. (1989). Sterilization of medical disposable devices with electron beam vs. Cobalt 60. *International Journal of Radiation Applications and Instrumentation Part C. Radiation Physics and Chemistry* **33**(2): 179–180.
47. Ruiging, Z. and Yongling, J. (1990). Development of radiation sterilization of medical products in China. *International Journal of Radiation Applications and Instrumentation Part C. Radiation Physics and Chemistry* **35**: 373–376.
48. Gagues containing radioactive isotope.
49. Kastenberg, W.E. and Wilson, R. (2004). Risk of nuclear power space probes. *Reliability Engineering & System Safety* **86**(1): 53–59.
50. International Commission on Radiological Protection, *ICRP 82: Protection of the Public in Situation of Prolonged Radiate, ICRP, 0080438989*, Pergamon-01-AUG-00 (Edition), ICRP.
51. Glasstone, S. (Ed.) (1964). *The Effects of Nuclear Weapons*, Revised Edition, Washington, DC: USAEC.

52. Hoffman, F.O. (1999). Advances in environmental dose reconstruction. *Radiation Research* **151**: 108–109.
53. UNSCEAR United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (2003). *Report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly*, Annex C.
54. Shipler, D.B., Napier, B.A., Farris, W.T., *et al.* (1996). Hanford environmental dose reconstruction project — an overview. *Health Physics* **71**(4): 532–544.
55. Degteva, M., Kozheurov, V., and Vorobiova, M. (1994). General approach to dose reconstruction in the population exposed as a result of the release of radioactive wastes into the Techa River. *Science of the Total Environment* **142**: 49–61.
56. http://www.who.int/ionizing_radiation/en/, last viewed 10-9-2013.
57. Fetter, S. and von Hippel, F. (1999). The hazard posed by depleted-uranium munitions. *Science and Global Security* **8**(2): 125–161.
58. Agency for Toxic Substances and Disease Registry (ATSDR) (1999). *Toxicological Profile for Uranium*, Atlanta, GA: US Department of Health and Human Services, Public Health Service.
59. World Health Organization (WHO) (2001). *Depleted Uranium Mission to Kosovo*, January 22–31.
60. Nordic Council of Ministers (1994). *Cleanup of Large Radioactive-contaminated Areas and Disposal of Generated Wastes*, Final Report of the KAN2 Project, TemaNord 1994:567, NCM, Copenhagen.
61. United States Department of Energy (1996). *Characterization, Monitoring and Sensor Technology Crosscutting Program*, Technology Summary, USDOE Rep. DOE/EM-0298, Washington, DC.
62. International Commission On Radiological Protection (1990). *Recommendation of the International Commission on Radiological Protection*, ICRP Publication 60, Vol. 21, No. 1–3, Annals of the ICRP, Oxford: Pergamon Press.
63. International Atomic Energy Agency (1998). *Application of Radiation Protection Principles to the Cleanup of Contaminated Sites, Areas*, Interim Report for comment. IAEA TecDoc-987, Vienna: IAEA.
64. Kholosha, V.I., Koval'skij, N.G., and Babich, A.A. (1996). Social, economic, institutional and political impacts. Report for Ukraine. In: *One Decade after Chernobyl. Summing Up the Consequences of the Accident. Proceedings of an International Conference*, Vienna, 1996. STI/PUB/1001. Vienna: IAEA, pp. 429–444.
65. Rolevich, I.V., Kenik, I.A., Babosov, E.M., *et al.* (1996). Social, economic, institutional and political impacts. Report for Belarus. In: *One Decade after Chernobyl. Summing Up the Consequences of the Accident. Proceedings of an International Conference*, Vienna, 1996. STI/PUB/1001. Vienna: IAEA, pp. 411–428.
66. Voznyak, V.Ya. (1996). Social, economic, institutional and political impacts. Report for the Soviet period. In: *One Decade after Chernobyl. Summing Up the Consequences of the Accident. Proceedings of an International Conference*, Vienna, 1996. STI/PUB/1001. Vienna: IAEA, pp. 369–378.
67. Voznyak, V.Ya. (1996). Social, economic, institutional and political impacts. Report for the Russian Federation. In: *One Decade after Chernobyl. Summing Up the Consequences of the Accident. Proceedings of an International Conference*, Vienna, 1996. STI/PUB/1001. Vienna: IAEA, pp. 379–410.

68. WHO Expert Group Report (2006). *Health Effects of the Chernobyl Accident and Special Health Care Programmes: Report of the UN Chernobyl Forum Health Expert Group*, B. Bennett, M. Repacholi, and Z. Carr (Eds.), Geneva: World Health Organization.
69. TEPCO, A One-year Review of Fukushima Daiichi Nuclear Power Station "Steps to Achieve Stabilization", last viewed 10-9-2013. http://www.tepco.co.jp/en/nu/fukushima-np/review/index-e.html
70. The international nuclear and radiological event scale (INES), http://www.iaea.org/Publications/Factsheets/English/ines.pdf, last viewed 10-9-2013.
71. International Atomic Energy Agency (2001). *Energy, Electricity and Nuclear Power Estimates for the Period up to 2020*, July 2000 Edition, Reference Data Series No. 1, Vienna: IAEA.
72. UNSCEAR United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (2003). *Report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly*, Annex E.
73. Site Investigation for Highway Works on Contaminated Land, HA 73/95, http://www.standardsforhighways.co.uk/dmrb/vol4/section1/ha7395.pdf, last viewed 10-9-2013.
74. Vandenhove, H., *et al.* (2000). *Investigation of a Possible Basis for a Common Approach with Regard to the Restoration of Areas Affected by Lasting Radiation Exposure as a Result of Past or Old Practice or Work Activity — CARE*, Final Report to the European Commission, Contract 96-ET-006, Radiation Protection, Vol. 115, p. 242, http://ec.europa.eu/energy/nuclear/radiation_protection/doc/publication/115.pdf, last viewed 10-9-2013.
75. International Atomic Energy Agency (2003). *Extent of Environmental Contamination by Naturally Occurring Radioactive Material (NORM) and Technological Options for Mitigation*, Technical Report Series 419, IAEA.
76. International Convention on Nuclear Safety.
77. Joint Convention on the Safety of Spent Nuclear Fuel Management and on the Safety of Radioactive Waste Management.
78. Euratom (1996). Council Directive 96/29/Euratom of 13 May laying down basic safety standards for the health protection of the general public and workers against the dangers of ionizing radiation, Official Journal of the European Communities L-159 of 29/06/1996, Luxembourg.
79. OSPAR Convention for the Protection of the Marine Environment of the North–East Atlantic. last viewed 29-8-2013. http://www.ospar.org/html_documents/ospar/html/ospar_convention_e-updated_text_2007.pdf
80. Report of the united nations conference on environment and development Rio de Janeiro.
81. International Atomic Energy Agency, *Basic Safety Standards for Protection against Ionizing Radiation and the Safety of Radiation Sources*, IAEA Safety Series No. 115.
82. International Atomic Energy Agency (2000). *Regulatory Control of Radioactive Discharges to the Environment Safety Guide*, IAEA Safety Standards Series No. WS-G-2.3.
83. Wang, Canfa (2007). Chinese environmental law enforcement: current deficiencies and suggested reforms. *Vermont Journal Of Environmental Law* **8**: 159–190.
84. (56 FR 23360-23474).

85. NCRP (2005). *Performance Assessment of Low-Level Waste Disposal Facilities*, Bethesda, MD: U.S. National Council on Radiation Protection and Measurements.
86. Vasseur, D. and Llory, M. International survey on PSA figures of merit. *Reliability Engineering and System Safety* **66**: 261–274.
87. Van Der Brost, M. and Schoonakker, H. (2001). An overview of PS importance measures. *Reliability Engineering and System Safety* **72**: 241–245.
88. International Atomic Energy Agency (1997). *Application of Radiation Protection Principles to the Cleanup of Contaminated Areas*, IAEA TECDOC-987, Vienna: IAEA.
89. International Atomic Energy Agency (1996). *International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources*, IAEA Safety Series No. 115, Vienna: IAEA.
90. International Atomic Energy Agency (1989). *Principles for the Establishment of Upper Bounds to Doses to Individuals from Global and Regional Sources*, IAEA Safety Series No. 92, Vienna: IAEA.
91. International Atomic Energy Agency (1992). *Establishment of Source Related Dose Constraints for Members of the Public*, Interim report for comment, IAEATECDOC-664, Vienna: IAEA.
92. International Atomic Energy Agency (2002). *Non-technical Factors Impacting on the Decision Making Processes in Environmental Remediation*, IAEA-TECDOC-1279, Vienna: IAEA.
93. Merkhofer, M.W.A. and Keeney, R.L. (1987). A multiattribute utility analysis of alternate sites for the disposal of nuclear waste. *Risk Analysis* **7**(2): 173–194.
94. International Atomic Energy Agency (1998). *Characterization of Radioactively Contaminated Sites for Remediation Purposes*, IAEA-TECDOC-1017, Vienna: IAEA.
95. International Atomic Energy Agency (1999). *Technologies for Remediation of Radioactively Contaminated Sites*, IAEA-TECDOC-1086, Vienna: IAEA.
96. U.S. Environmental Protection Agency (1996). *Technology Screening Guide for Radioactively Contaminated Sites*, EPA 402-R-96-017.
97. Hugh Mallett (2004). *Technical Options for Managing Contaminated Land*, CIRI-6349A, CR0117001.
98. International Atomic Energy Agency (1999). *Technical Options for the Remediation of Contaminated Groundwater*, IAEA-TECDOC-1088, Vienna: IAEA.
99. International Atomic Energy Agency (1999). *State of the Art Technology for Decontamination and Dismantling of Nuclear Facilities*, Technical Report Series 395.
100. International Atomic Energy Agency (1988). *Decontamination and Demolition of Concrete and Metal Structures During the Decommissioning of Nuclear Facilities*, Technical Reports Series 286, Vienna: IAEA.
101. ANTIOXI (2008). Decontamination techniques for activity removal in nuclear environments, NO VTTR0029908|12.3.2008, Research Report R0029908.
102. (1982). Comparison of decontamination techniques for reactor coolant system applications, EPRI Report NP2777.
103. International Atomic Energy Agency (2001). *Minimization of Radioactive Waste from Decontamination and Decommissioning of Nuclear Facilities*, Technical Reports Series 401, Vienna: IAEA.

104. U.S. EPA (2006). *Technology Reference Guide for Radiologically Contaminated Surfaces*, EPA-402-R-06-003. Washington, DC, Office of Air and Radiation, www.epa.gov/radiation/docs/cleanup/402-r-06-003.pdf, last viewed 10-9-2013.
105. International Atomic Energy Agency (1970). *Standardization of Radioactive Waste Categories*, Technical Reports Series No. 101, Vienna: IAEA.
106. Phillips, J. (1979). *A Waste Inventory Report for Reactor and Fuel Fabrication Facility Wastes*, Rock Well, Maryland, the USA: NUS Corporation.
107. Abdel Rahman, R.O., El-Kamash, A.M., Shehata, F.A., and El Sourougy, M.R. (2007). Planning for a solid waste management quality assurance program in Egypt. *The Quality Assurance Journal* **11**: 53–59.
108. International Atomic Energy Agency (1984). *Treatment of Spent Ion-Exchange Resins for Storage and Disposal*, Technical Reports Series No. 254, Vienna: IAEA.
109. International Atomic Energy Agency (1992). *Chemical Precipitation Processes for the Treatment of Aqueous Radioactive Waste*, Technical Reports Series No. 337, Vienna: IAEA.
110. Abdel-Halim, H.A., Zaki, A.A., El-Kamash, A.M., and Othman, E.A. (2005). In: *Proceedings of the Third Minia International Conference for Advanced Trends in Engineering*, April 3–5, Volume II, p. 304.
111. El-Kamash, A.M., Abdel-Halim, H.A., and Zaki, A.A. (2006). In: *Proceedings of the 6th International Conference on Role of Engineering towards Better Environment*, Alexandria, RETBE 06, Egypt, December 16–18.
112. International Atomic Energy Agency (2000). *Management of Radioactive Waste from the Use of Radionuclides in Medicine*, IAEA-TECDOC-1183, Vienna: IAEA.
113. International Atomic Energy Agency (1995). *The Principles of Radioactive Waste Management*, Safety Series No. 111-F, Vienna: IAEA.
114. Abdel Rahman, R.O., El-Kamash, A.M., Zaki, A.A., and El Sourougy, M.R. (2005). In: *Proceedings of the International Conference on the Safety of Radioactive Waste Disposal*, Tokyo, Japan, p. 317.
115. International Atomic Energy Agency (1999). *Review of the Factors Affecting the Selection and Implementation of Waste Management Technologies*, IAEA-TECDOC-1096, Vienna: IAEA.
116. International Atomic Energy Agency (2003). *Appraisal for Brazil of the Safety of the Transport of Radioactive Material, IAEA Safety Standards Applications — TranSAS-2 Provision for the Application of the IAEA Safety*, Vienna: IAEA.
117. International Atomic Energy Agency (1994). *Advances in Technologies for the Treatment of Low and Intermediate Level Radioactive Liquid Wastes*, Technical Reports Series No. 370, Vienna: IAEA.
118. Abdel Rahman, R.O., El-Kamash, A.M., Ali, H.F., Yung-Tse Hung (2011). Overview on Recent Trends and Developments in Radioactive Liquid Waste Treatment Part I: Sorption/Ion Exchange Technique, *International Journal of Environmental Engineering Science*, **2**(1): 1–16.
119. International Atomic Energy Agency (1992). *Treatment and Conditioning of Radioactive Solid Wastes*, IAEA-TECDOC-655, Vienna.
120. Abdel Rahman, R.O., El-Kamash, A.M., and Zaki, A.A. (2007). Modeling the long term leaching behavior of 137Cs, 60Co, and152,154Eu radionuclides from cement-clay matrices. *Journal of Hazardous Materials* **145**: 372–380.

121. International Atomic Energy Agency (1999). *Near Surface Disposal of Radioactive Waste*, Safety Standards Series No. WS-R-1, Vienna: IAEA.
122. International Atomic Energy Agency (1995). *Sitting of Near Surface Disposal Facilities*, Safety Series No. 111. G3.1.
123. International Atomic Energy Agency (2002). *Socio-economic and Other Non-radiological Impacts of the Near Surface Disposal of Radioactive Waste* TecDoc 1308, Vienna: IAEA.
124. International Atomic Energy Agency (1984). *Design, Construction, Operation, Shutdown and Surveillance of Repositories for Solid Radioactive Wastes in Shallow Ground*, Safety Series No. 63, Vienna: IAEA.
125. Gupta, M.P., Mondal, N.K., Bodke, S.B., and Bansal, N.K. (1997). Indian experience in near surface disposal of low level radioactive solid wastes, *Planning and Operation of Low Level Waste Disposal Facilities* (Proc. Int. Symp., Vienna, 1996). Vienna: IAEA, pp. 275–284.
126. Sakabe, Y. (year). Design concept and its development for the Rokkasho low level waste disposal centre, *ibid.*, pp. 123–284.
127. International Atomic Energy Agency (2003). *Safety Considerations in the Disposal of Disused Sealed Radioactive Sources in Borehole Facilities*, IAEA-TECDOC-1368, Vienna: IAEA.
128. International Atomic Energy Agency (2001). *Derivation of Activity Limits for Disposal of Radioactive Waste to Near Surface Facilities, Draft Working Material*, Version 0.3, Vienna: IAEA.
129. International Atomic Energy Agency (1996). *Requirements and Methods for Low and Intermediate Level Waste Package Acceptability*, IAEA-TECDOC-864, Vienna: IAEA.
130. Miller, W., *et al.* (2000). *The Structure, Content and Presentation of a Safety Case for a Geological Disposal Facility* (Contractor Report). Harwell: UK Nirex Limited.
131. British Nuclear Fuels Limited (2000). Status Report on the Development of the 2002 Drigg Post-Closure Safety Case, BNFL, Sellafield.
132. International Atomic Energy Agency (1999). *Safety Assessment for Near Surface Disposal of Radioactive Waste*, Safety Standards Series No. WS-G-1.1, Vienna: IAEA.
133. International Atomic Energy Agency, (2004). Safety Assessment Methodologies for Near Surface Disposal Facilities. Results of a Co-ordinated Research Project. Volume I: Review and Enhancement of Safety Assessment Approaches and Tools. International Automic Energy Agency, Vienna, 2004.
134. ICRP Publication (2000). Radiation Protection Recommendations as Applied to the Disposal of Long-lived Solid Radioactive Waste, 81.
135. Swedish National Council for Nuclear Waste (1999). Nuclear Waste State-of the-Art Reports 1998, Stockholm: KASAM.
136. International Atomic Energy Agency (2000). *Confidence Building in the Safety Assessment of Near Surface Radioactive Waste Disposal Facilities*, ISAM/CBWG/WD01, Vienna: IAEA.
137. Savage, D. (Ed.) (1995). *The Scientific and Regulatory Basis for the Geological Disposal of Radioactive Waste*, New York: Wiley.