# ENVIRONMENTAL EFFECTS OF NUCLEAR POWER GENERATION

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## Contents



## Summary

The system of dose limitation to control public exposure to radiation exposure, which is adopted almost universally, is briefly presented and discussed for the case of nuclear power generation. The limits of public exposure recommended by the International Commission on Radiological Protection (ICRP) and those adopted for routine operation of light water reactors (LWRs) are also presented. Criteria for site selection, construction and design of are briefly mentioned, as well as procedures for emergency planning, preparedness and response to nuclear accidents. The basic principles that underline the production of nuclear energy is discussed succinctly. The conditions to achieve a nuclear chain reaction are discussed with a view to its application to nuclear reactors and power generation. The environmental effects of nuclear power generation are examined from the construction of a nuclear power plant and its ancillary operations up to environmental impact assessments concerning the transportation of commercial spent fuel to reprocessing facilities, or to interim repositories, passing through several environmental impacts, for example, thermal discharges. Along the way the ALARA (as low as reasonably achievable) criterion adopted for the releases of radioactive effluents during the routine operation of nuclear power plants is examined. A potential inventory of fission and corrosion products, and actinides in spent nuclear fuel is summarized in three tables to be used as a basis for preliminary estimates in the case of a major nuclear accident.



## 1. Introduction

The nuclear power generation constitutes the intermediate phase between the front- and back-ends of the nuclear fuel cycle. There are in this intermediate phase routine

releases of radionuclides to the surrounding environment in liquid and gaseous forms. As far as the environmental effects of these routine releases are concerned a system of dose limitation to control public exposure to radiation is adopted in mostly all cases. This system of dose limitation is based in a tripod which includes the justification of a practice, the optimization of protection of public exposure, and dose limits for public exposure. Usually the concept of collective effective dose per unit of practice is used in the justification of a practice and in the optimization of protection. In the case of nuclear power generation the unit of practice is the unit of electrical energy generated, that means MW(e); while the unit of collective effective dose is man.sievert (man.Sv). It should be noted, however, that part of the collective dose may be received somewhere in the future. The concept of effective dose commitment to a critical group of individuals is then introduced to further limit future individual doses (that means, doses to typical members of a critical group). Moreover, in the case of exposures to the members of the public, when dose limits are used as constraints for optimization, one should be aware that some conceptual difficulties will appear. Optimization is a source-related requirement, while a dose limit is essentially an individual-related requirement. To avoid that a single practice be inhibit, for example the construction of a second nuclear power plant in the same site where there is one, even when optimization would allow it, small fractions of the dose limit should be allocated to each practice. Thus, exposures from more than one practice would be allowed to overlap.

Fission and corrosion products are in the primary coolant of nuclear reactors in a variety of concentrations. When one assumes that a fraction of one percent of the fuel fails, and a leak occurs at a small rate across the heat exchanger, trace amounts of fission and corrosion products find their way to the steam generator (or the secondary system). Some of these trace radionuclides present in the primary and/or secondary coolant loops may be released in several ways, including, for example, pressurizers, steam valves, seals, and pipes. The atmosphere of the nuclear reactor containment vessel retains the gaseous and volatile radionuclides, while the liquid ones go to floor drains and retention tanks. A system of radioactive waste treatment and retention, the Radwaste system, is design to work in such a way that most of the radionuclides in the containment vessel and in the retained tanks are not released. However, small amounts are released in accordance with the ALARA principle. This means that releases are to be made in a way "to ensure that the magnitude of the individual doses, the number of people exposed, and the likelihood of incurring exposures where these are not certain to be received, are all kept as low as reasonably achievable , economic and social factors being taken into account."

By and large, annual averages of the effective dose equivalent received due to nuclear power generation in the world are of the order of $0.1 \mu Sv.y^{-1}$, while the annual dose limits adopted for light water reactors (LWRs) lie between 0.10 and 0.25 $mSv.y^{-1}$. This means that the world annual averages are less that one thousandth the adopted limits for nuclear power generation. Moreover. The International Commission on Radiological Protection (ICRP) recommends that the limit for public exposure should be $1mSv.y^{-1}$. A higher value of annual effective dose can be allowed in one single year, however, provided that the average over 5 years does not exceed $1mSv.y^{-1}$.

One aspect of the routine releases of radionuclides from nuclear power generation deserves further attention. Three radionuclides, $^{3}H$, $^{85}Kr$ and $^{14}C$ with half-lives 12.3 years, 10.7 years, and 57,300, respectively, are emitted in gaseous or liquid phases. Because their long half-lives these radionuclides accumulate and circulate in the global environment. Studies on the long term environmental effects of nuclear power generation will need to take into account the overall releases of $^{3}H$, $^{85}Kr$ and $^{14}C$.

The site of construction of a nuclear power plant should always be chosen to minimize the effects of a potential accident. Before constructing a nuclear power plant in any particular site data are gathered on the local meteorology, population density in the surrounding areas, existing crops, and orography. Such data will be used to make site specific analyses involving real time estimation of accident consequences. Design reactors engineers estimate that a probability of occurring an accident with a nuclear power plant is very low, because they trust the multiple levels of protection against reactor and/or containment failures with significant radionuclide releases. However, models are also selected for calculating doses, health effects, and economic costs due to accidental radionuclide releases from nuclear power plants. Moreover, there are established criteria for preparation and evaluation of radiological emergency response plans and preparedness in support of nuclear power plants.

Atmospheric and terrestrial food-chain transport models are prepared to estimate air concentrations at ground levels and ground contamination concentrations at off-site locations resulting from accidental releases of radionuclides to the atmosphere. An accident may release significant amounts of , for example, $^{131\text{-}135}I$, $^{131m,\ 132}Te$, $^{134}Cs$, and $^{88}Kr$ into the atmosphere. The atmospheric pathway will bring these and other gaseous radionuclides into a radioactive plume to be deposited on the ground and to become available for direct inhalation within a short time after an accident. Dose estimates due to short term inhalation are subject to great uncertainties, because the source term is seldom well known. Emergency planning should also contemplate coordinated actions based on the available information to classify the accident and to evaluate the potential off-site consequences and countermeasures to minimize the theoretically predicted consequences. In addition, both short-term and long-term environmental monitoring are required to provide input for models in which decision-making personal base their actions. Personnel monitoring is also required when there are indications that inhalation or ingestion of radionuclides might have occurred. The overall objective of emergency preparedness and response is to prevent or keep to a minimum the radiation dose to the public and workers.



## 2. Nuclear energy

Whenever a reaction occurs in which the atomic number, mass number or radioactivity of the atomic nucleus changes energy is released. This kind of nuclear energy arises from the special forces that hold the positive proton and the neutral neutron within the small volume of the atomic nucleus. These special forces are a million times stronger than the chemical bonds that hold together molecules. The binding energy BE that maintains together the components of a stable nucleus is equivalent to the so called mass defect, expressed as $BE = \Delta m.c^2$, where c is the electromagnetic constant (the speed of light in a vacuum). The BE is equivalent to the work needed to split up the

nucleus into separate protons and neutrons, and is always positive. The BE varies with the size of the nucleus, that means with the number of protons and neutrons in its interior. The BE is lower for very lighter elements, increasing steeply as Z increases. Thus, energy can be released by combining two deuterium nuclei to form a helium nucleus. This combination is known as a fusion reaction. The BE curve passes through a maximum at intermediate nuclei, and decreases for heavier nuclei. This means that at some point intermediate nuclei form the most stable elements. For heavier nuclei the BE decreases, indicating that the more positively charged the nucleus becomes, the less stable it is. As a matter of fact, this is why there are not very heavy elements in nature, and all elements heavier than bismuth are naturally unstable (i.e., radioactive). Just before the beginning of WWII it was observed that when the heavy element uranium was bombarded with slow neutrons a violent reaction occurred. This striking phenomenon was correctly interpreted not too much later as the fission of $^{235}U$ (a less abundant naturally occurring uranium isotope) into two or more lighter elements with release of high amount of energy. One fission is always accompanied by the emission of two or more neutrons, because the neutron-to-proton-ratio of each fission product is lower than that of the that of uranium. The emission of more than two neutrons per fission is the key for the of the energy released by the fission either for military use or power generation. A chain reaction. A nuclear chain reaction is achieved when neutrons released by a preceeding fission are absorbed by surrounding fissile nuclei maintaining an indefinite fission chain. Nuclear energy from fission and fusion have already been used in military weapons, however, only fission has been used as a controlled source for power generation thus far.

## 3. Nuclear reactors and power generation

After being used to develop military weapons during World War II (WWII), nuclear energy from fission was tamed to be used for peaceful purposes, including for power generation in nuclear power plants. The mostly widely used nuclear reactor type in a power plant is the light water reactor (PWR). The LWR uses light water as a moderator to slow down the neutrons speed in the core to increase the efficiency of the fission process. The process of fission is one in which an atomic nucleus breaks up into two or more major fragments with the emission of neutrons. The fission of $^{235}U$ can be induced by the absorption of a slow neutron. Fission is accompanied by the release of energy in the form of gamma radiation and the kinetic energy of the emitted particles, manifested as heat. The heat converts water into steam, which drives turbo-alternators to generate electricity. The fuel of a nuclear reactor is usually uranium pellets, usually enriched in the isotope $^{235}U$ up to about 3.5%, surrounded by a moderator and a cooling fluid. In the LWR water plays the dual role of moderator and cooling fluid. There are two types of nuclear types of LWRs, the pressurized water reactor (PWR), and the boiling water reactor (BWR).

The PWR operates under a pressure high enough to ensure that the water circulating in the primary cooling system and passing through the reactor core does not boil. This high temperature (well above 100°C) and high pressure water passes through a steam generator that contains water of the secondary system that is transformed in steam, which in turn is used to drive the turbine-alternator assembly to generate electricity. After passing through the turbine the steam is driven through a condenser to be again

transformed into water to circulate in the secondary system. FIGURE 1 is a schematic representation of a typical PWR with its primary coolant and secondary systems plus turbine and electricity generator.

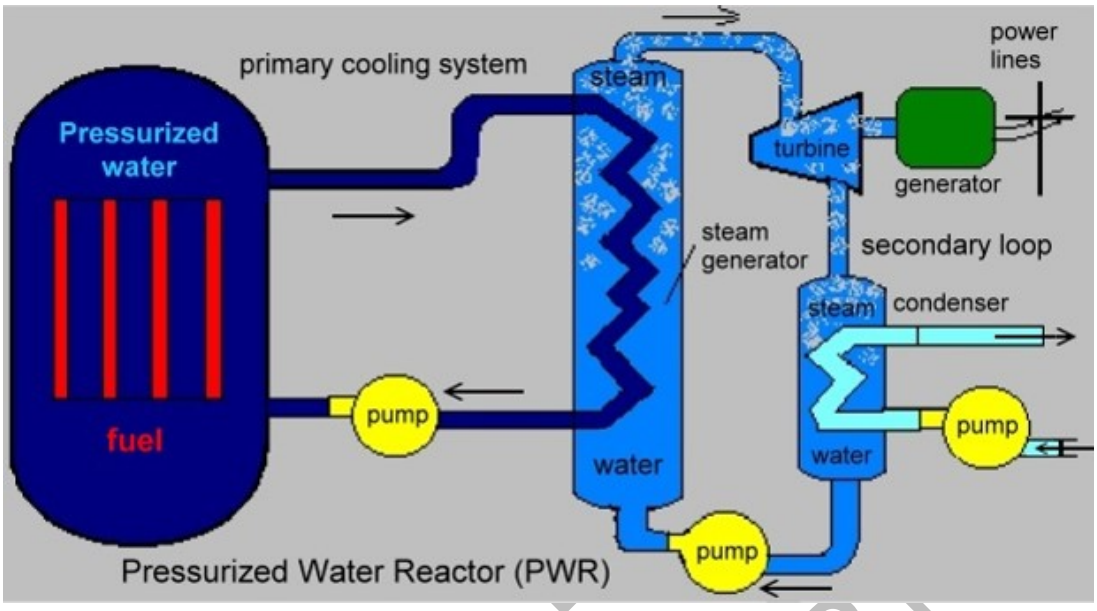


Figure 1.Simplified scheme of a pressurized water reactor (PWR) based nuclear power plant.

In the BWR the water boils partially as it circulates through the reactor core. The steam so produced is used to drive the turbine-generator assembly to generate electricity. A BWR plant operates, apart with the nature of the fuel, in a fashion similar to a fossil fuel plant. The BWR does not have the advantage of a single phase coolant system, as it does the PWR. FIGURE 2 is a schematic representation of a typical BWR with its cooling water-steam system plus turbine and electricity generator.

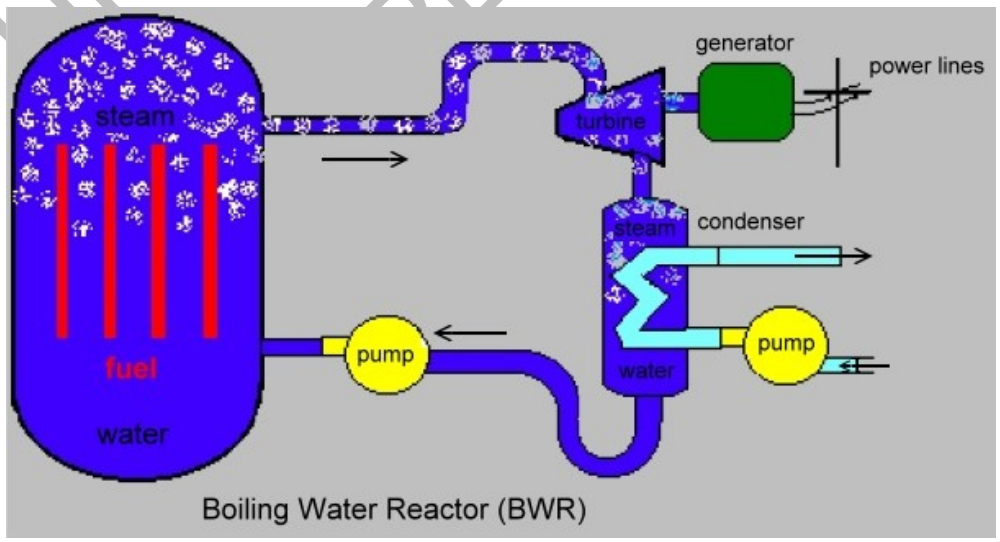


Figure 2.Simplified scheme of a boiling water reactor (BWR) based nuclear power plant.

There are several other types of nuclear reactors, using a variety of coolants and moderators. All of them, however, must contain sufficient fissionable or fissile material, arranged in an appropriate configuration that a controlled chain reaction can be started up and be maintained. All types of reactors produce neutrons, gamma rays, radioactive fission and corrosion products, actinides, and heat. Large amounts of kinetic energy and heat are produced in the process of fission of a heavy nucleus. The heat so produced is used to carry out a variety of high-temperature processes or for heating a working fluid to operate a turbine and produce electricity. Other than the LWRs, the most common nuclear reactors types are the following:

(i) the heavy water reactor (HWR), which uses heavy water as moderator and uranium with the natural $^{235}U$ abundance as nuclear fuel;
(ii) the fast reactors (FR), which does not have moderators, the nuclear fuel can be either $^{235}U$ or $^{239}Pu$, can breed by producing new nuclear fuels such as $^{239}Pu$ or $^{233}U$ through absorption of neutrons by $^{238}U$ and $^{232}Th$, respectively, and may be cooled by liquid metal (LMFBR) — liquid sodium, for example — or gas (GCFR), which uses superheated steam, carbon dioxide, or helium;
(iii) the magnox reactor, which uses uranium with its natural isotopic abundance as a fuel contained in metallic rods sealed in cans made of magnesium alloy with beryllium and aluminum (magnox), graphite is the moderator, and carbon dioxide is the cooling agent;
(iv) the water cooled graphite moderator reactor (RBMK) was developed in the former Soviet Union first to produce plutonium for military programs, and later larger versions to generate electricity also; and
(v) the modular high-temperature gas-cooled (MHTGR) and the process inherent ultimate safety (PIUS) are part of a new generation of reactors being developed for future power generation.

## 4. Environmental effects

A nuclear power plant starts disturbing the environment during the plant construction. This kind of disturbance, however, is a common problem to any major enterprise, as for example, a non-nuclear power plant. Normal processes of plant construction as well as ancillary operations, not necessarily related to the nuclear nature of the power plant fuel, do disturb the surrounding environment. New roads, increasing traffic flow in the existing roads, excavations, cutting trees and other plants, frightened animals, are some of the environmental impacts to be expected from the construction of a power plant. In the case of a hydroelectric plant a large man-made lake which will replace free-flowing rivers is also to be built. In addition to all those impacts the builders of power plants should minimize, under the guidance of the legally competent authorities, disturbance to any prehistoric petrified plants and animals or to any archeological remains of early civilizations, graveyards, monuments, ruins, aqueducts and so on. Site selection for nuclear power plants should be carefully made to avoid, or minimize to the extent possible, most of those impacts.

Thermal discharges of unused heat from fossil fuel or from fission in the nuclear fuel constitute another kind of environmental impact. Thermal effects in biota include problems with reproduction, growth, survival of larval forms, juveniles and adults.

Regulatory agencies establish water temperature standards to govern heated discharges from the power plants to prevent catastrophic kills to occur, or thermally induced demise of aquatic populations. Fish, plankton and benthos are all affected at various degrees by thermal discharges from power plants.

Other environmental impact common to all nuclear power plants are the highly visible transmission lines associated with the generation and distribution of electricity. Underground cables are not yet an economically feasible solution for most cases of transmission of electricity.

Radioactive effluents released from nuclear power plants are, however, the main object of monitoring and control to minimize exposure of the public to ionizing radiation. There are a wide variety of nuclear reactor types, as it was discussed in subsection 4 of section 4.3.3. *Environmental Effects of Nuclear Power Production*. However, most of the operating nuclear reactors are light water reactors (LWRs), either pressurized water reactors (PWRs) or boiling water reactors (BWRs). Thus, the discussion here will be restricted to the sources of radioactivity from these two types of reactors only.

In the years 1973 and 1974 the normalized tritium gas releases from PWRs were reported for 21 nuclear power plants to range from approximately 1MBq.MW(e)$^{-1}$.y$^{-1}$ to about 40,000 MBq.MW(e)$^{-1}$.y$^{-1}$. For BWRs the range for the same two years in 14 nuclear power plants was from 4 MBq.MW(e)$^{-1}$.y$^{-1}$ to 90,000 MBq.MW(e)$^{-1}$.y$^{-1}$.

While the nuclear fuel is still being burned in the reactor, releases of radionuclides in liquid and gaseous phases are made routinely based on the ALARA criterion, as it was mentioned in the introduction of this section. This means that a radioactive treatment system should be able to decrease the radioactivity of any particular radionuclide to levels consistent with the adopted criterion. Contaminated liquids are stored and allowed to decay for a time. The stored time is long enough so the radioactivity of short lived radionuclides becomes trivial. In addition, decontamination factors are obtained with a series of chemical and physical operations. The iodine isotope $^{131}$I is considered to be critical in the case of an accident, so it is important to know its activity and decontamination factor at every stage of the radioactive treatment system. After the Three Mile Island accident $H_2$ and HT (tritiated hydrogen) are converted into water to minimize the probability of hydrogen explosions. Noble gas activity is reduced by maintaining the gases up to three days in delay tanks. This procedures removes the radioactivity of the short lived isotopes of xenon and krypton, leaving mostly $^{133}$Xe (5 days half-life) and $^{85}$Kr (10 days half-life) as the main gaseous radionuclides to be released into the environment. Estimated gaseous releases of isotopes of xenon and krypton are of the order of terabecquerels per year (TBq.y$^{-1}$), based on 0.25% failed fuel. Xenon and krypton releases, and to a lesser extent tritium, dominate the routine gaseous releases in nuclear power plants. As far as liquid releases are concerned, tritium is by far the most dominant radionuclide released routinely. In terms of radioactivity, liquid routine releases of all other radionuclides combined correspond only about 1% of that released by tritium discharges. The movement of radionuclides in the environment depends on several factors, like point of release, rate of release, chemical form, natural structure of the surrounding environment, among others.

Environmental impact assessments include also transportation of commercial spent fuel to reprocessing facilities, or to interim repositories when no immediate reprocessing is the policy adopted, as it is the case of the United States. Usually the minimum cooling time required for transportation of spent fuel is 150 days. There are significant quantities of fission products, actinides, and corrosion products in spent reactors fuels. TABLES 1, 2, and 3 summarize, respectively, the fission products, actinides, and corrosion products contents of spent nuclear fuel after a burn up of 33 GWd.(metric ton)$^{-1}$ and 150 days cooling time. The knowledge of the contents of spent nuclear fuel at any given time is important because of potential releases in the case of accident during transportation. The high activity of $^{106}$Ru (1 year half-life) in spent nuclear fuel, for example, needs special attention because $RuO_4$ is a volatile oxide, making it necessary to retain it for as long as possible to allow decay. Rules and regulations that govern transportation of spent nuclear fuels are such that about 300,000 TBq are transported per year without any major accident thus far. The regulatory requirements depend on the type of vehicle being used, the kinds and the amount of radionuclides involved. Shipments of spent nuclear fuel, high level radioactive wastes, or large amounts of transuranic wastes require a very high degree of physical protection, as well as well shielded transportation casks that will hold their integrity in the case of an accident to prevent any public exposure to ionizing radiation or toxic materials. Although there have been some accidents with shipments of radioactive materials, mostly radio-pharmaceuticals, with activities less than 1 TBq, there is not any confirmed report of accidents with casks used to ship spent fuels. These casks should be able to withstand a 9 m drop to a hard surface, a fall of more than 1 m, landing on the upraised tip of a 15 cm diameter steel bar, at least 8 hour submersion under 1 m of water, and a 30 min exposure to a temperature of 802°C.

| Fission product | Half-life (years) | TBq.(metric tons)$^{-1}$ | g.(metric tons)$^{-1}$ |
|---|---|---|---|
| $^{3}$H | 12 | 32 | 0.08 |
| $^{85}$Kr | 11 | 420 | 27 |
| $^{99}$Tc | 0.21 million | 0.6 | 880 |
| $^{103}$Ru | 0.11 | 7,200 | 5.7 |
| $^{106}$Ru | 1.0 | 33,000 | 240 |
| $^{125m}$Te | 0.16 | 260 | 0.36 |
| $^{127m}$Te | 0.30 | 1,000 | 2.7 |
| $^{129m}$Te | 0.09 | 530 | 0.42 |
| $^{129}$I | 17 million | 0.0016 | 250 |
| $^{131}$I | 0.02 | 0.08 | < 0.01 |
| $^{134}$Cs | 2.0 | 4,000 | 77 |
| $^{135}$Cs | 3 million | 0.048 | 1,400 |
| $^{137}$Cs | 30 | 4,200 | 1200 |
| $^{89}$Sr | 0.14 | 4,000 | 3.5 |
| $^{90}$Sr | 29 | 2,400 | 430 |
| $^{91}$Y | 0.16 | 7,600 | 7.8 |
| $^{93}$Zr | 0.95 million | 0.08 | 490 |
| $^{95}$Zr | 0.18 | 16,000 | 19 |
| $^{95}$Nb | 0.10 | 32,000 | 21 |
| $^{125}$Sb | 2.7 | 520 | 12 |

| | | | |
|---|---|---|---|
| $^{141}$Ce | 0.09 | 3,200 | 2.8 |
| $^{144}$Ce | 0.78 | 32,000 | 250 |
| $^{147}$Pm | 2.6 | 8,000 | 220 |
| $^{155}$Eu | 5.0 | 1,600 | 87 |

[a] Based on 33 GWd(t).(metric ton)$^{-1}$ burn up, and 150 days cooling time.

Table 1. Fission products contents in spent nuclear fuel.

| Actinide | Half-life (years) | TBq.(metric ton)$^{-1}$ | g.(metric ton)$^{-1}$ |
|---|---|---|---|
| $^{235}$U | 710 million | < 0.04 | 8,000 |
| $^{236}$U | 24 million | < 0.04 | 4,000 |
| $^{238}$U | 450 million | < 0.04 | 950,000 |
| $^{237}$Np | 2 million | < 0.04 | 600 |
| $^{238}$Pu | 86 | 160 | 230 |
| $^{239}$Pu | 24,000 | 20 | 8,100 |
| $^{240}$Pu | 6,600 | 26 | 2,900 |
| $^{241}$Pu | 13 | 6,000 | 1,300 |
| $^{242}$Pu | 0.38 million | 0.08 | 510 |
| $^{241}$Am | 458 | 30 | 230 |
| $^{243}$Am | 7,800 | 0.8 | 100 |
| $^{242}$Am | 0.45 | 1,400 | 10 |

[a] Based on 33Gwd(t).(metric ton)$^{-1}$ burn up, and 150 days cooling time.

Table 2. Actinides contents in spent nuclear fuel.

| Corrosion products | Half-life (years) | TBq.(metric ton)$^{-1}$ | g.(metric ton)$^{-1}$ |
|---|---|---|---|
| $^{54}$Mn | 0.86 | 1,200 | 3.9 |
| $^{55}$Fe | 2.7 | 800 | 8.3 |
| $^{59}$Fe | 0.12 | 20 | < 0.01 |
| $^{58}$Co | 0.20 | 1,200 | 1.0 |
| $^{60}$Co | 5.3 | 80 | 1.8 |

[a] Based on 33 GWd(t).(metric ton)$^{-1}$ burn up, and 150 days cooling time.

Table 3. Corrosion products contents in spent nuclear fuel.

The non-linear decreases in the radioactivity of fission products, actinides and corrosion products that remain in irradiated fuels plus the different half-lives of the radionuclides involved make the exact prediction of the remaining activity at any given time after discharge from reactor a complex exercise. The radioactivity of spent fuels decrease steadily, but not at the same rate because of the differences in half-lives. Numerous computer codes have been developed to allow a pretty good estimate of the activity of any particular radionuclide in spent nuclear fuel long after leaving the reactor site. The overall radioactivity of spent nuclear fuels diminish more than one order of magnitude in the first 100 years, by a factor of 100 in the next 100 years, then another factor of 100 in the next 1,000 years. This means that a metric ton of non-reprocessed spent nuclear fuel with a total activity of about 25,000 TBq when it leaves a reactor will have a residual activity of 250,000 MBq (one million times less) ten million years later. During the first thousand years the greatest contribution to the radioactivity will be from the

beta and gamma emissions of the fission products $^{90}Sr$ and $^{137}Cs$. After that, most radioactivity will come from the very long lived alpha emitting actinides and their radioactive products. The total radioactivity in high-level waste from reprocessed spent nuclear fuel will be about one order of magnitude lower after the first thousand years, maintaining a similar difference subsequently. Heat in non-reprocessed spent fuel and in high-level wastes from reprocessing plants will decay from two to three orders of magnitude in the first thousand years. These characteristics of nuclear spent fuels and high-level wastes explain why it is necessary to work with a time horizon so much longer, when one has to deal with the back end of the nuclear fuel cycle.

## 5. Concluding remarks

1. Attention is called to the fact that an almost universally accepted system of dose limitation is used to control public exposure for the case of routine releases of radioactive effluents during power generation in nuclear power plants. Such system, based in a tripod which includes justification of a practice, optimization of protection of the public, and dose limits for public exposure. Moreover, the ALARA criterion (as low as reasonably achievable, economic and social factors taken into account) is adopted for the actual routine releases of radioactive effluents into the environment. This assures that, in the case of nuclear power generation, the magnitude of the individual doses, the number of people exposed, and the likelihood of incurring exposures are all kept ALARA.
2. Site selection and design of a nuclear power plant are made in such a way that in the case of a nuclear accident the radiological and radio-ecological effects are supposed to be held at a minimum. Although the probability of occurring serious accidents with a nuclear power plant are estimated by design reactors engineers to be very low, there are available models for calculating doses, health effects, and economic costs resulting from potential accidental radionuclide releases from nuclear power plants. Emergency planning and preparedness, as well as prompt response contemplate coordinated actions to classify each accident, to evaluate potential off-site consequences, and to apply countermeasures in order to avoid or keep to a minimum the theoretically predicted effects.
3. There are significant quantities of fission and corrosion products, as well as actinides in spent nuclear fuels. The knowledge of those quantities is important to evaluate potential releases at any given time, and during transportation of casks containing spent nuclear fuel. While spent nuclear fuel containing around 300,000 TBq are transported per year in special casks, no major accident has been reported thus far.
4. While one metric ton of non-reprocessed spent nuclear fuel with an initial activity of 25,000 TBq will have a residual activity one million times less after ten million years, high-level nuclear wastes from reprocessed spent nuclear fuel will have ten times less activity after the first thousand years, maintaining a similar difference subsequently. This means that the time horizon to which high-level nuclear wastes will have to be dealt with is well beyond any human experience.
5. By and large the environmental effects of nuclear power generation are fairly well understood, apart from those resulting from the high-level nuclear wastes.

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**Glossary**

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|---|---|
| absorbed dose **:** | the fundamental dosimetric quantity in radiological protection. It is the energy absorbed per unit mass. The unit of absorbed dose is the $J.kg^{-1}$, which is given the special name gray (Gy). |
| Actinides**:** | the fifteen elements with atomic numbers (Z) between 89 and 103, beginning with actinium. The actinides through uranium (Z = 92) occur in nature, while those with $93 \leq Z \leq 103$, the transuranium elements, are primarily synthetic although traces of some of them occur naturally. Among the actinides are thorium, uranium, and plutonium. |
| alpha particle**:** | a positively charged particle emitted from the nucleus of a radioactive atom. An alpha particle is identical with the nucleus of a helium atom. |
| atomic nucleus**:** | part of the atom constituted by positively charged protons and, apart from the hydrogen atom, uncharged neutrons, with a total charge *Ze*, mass M, and mass number A. |
| atomic number (Z)**:** | he number of protons in the nucleus of an atom. Each element has its unique atomic number which characterizes its chemical properties. The atomic number is also known as the proton number. |
| atomic weight (AW)**:** | the mean mass of the atoms of an element weighted according to the relative abundance of its naturally occurring isotopes and measured relative to some standard. Since 1961 the carbon isotope $^{12}C$ has been the standard, and its atomic mass is defined to be exactly 12. The atomic weight is also known as the relative atomic mass. |
| becquerel (Bq)**:** | the SI unit of radioactivity. 1 Bq equals 1 disintegration per second. |
| beta particles**:** | electrons or positrons emitted from radioactive nuclei undergoing spontaneous disintegration. Beta particles are emitted with velocities approaching that of the light and can penetrate up to 1 mm of lead. |
| beta ray**:** | a stream of beta particles. |
| binding energy (BE)**:** | the energy that holds together in a nucleus Z protons and Z-A neutrons, corresponding to the nucleon-nucleus mass difference. The average BE per nucleon increases with the atomic mass A reaching a maximum at around A = 60, with a gradual decrease from there on. |
| collective dose**:** | the sum of *per capita* dose for a given organ over the number of individuals exposed. |

Contamination**:** the presence of radioactive substances in or on a material or the human body or other place where they are undesirable or could be harmful.

corrosion product**:** a radionuclide produced in a nuclear reactor due to the absorption of neutrons in corroded metals or alloys present in core structures or tubes. Common examples of corrosion products are $^{54}$Mn, $^{58}$Co and $^{60}$Co.

counter-measure**:** an action aimed at alleviating the consequences of an accident.

cumulative dose**:** the sum of all annual doses over a selected period of years.

Deuterium**:** an isotope of hydrogen whose nucleus has one proton and one neutron. The molecule of heavy water is composed of one atom of oxygen plus two atoms of deuterium.

effective dose**:** is the sum of the weighted equivalent doses in all tissues and organs of the body.

equivalent dose**:** is the absorbed dose averaged over a tissue or organ and weighted for the radiation quality that is of interest.

Electron**:** a stable, negatively charged particle which is the constituent of all atoms. The electrons in each atom surround the nucleus in grouping called shells. The number of electrons in a neutral atom is equal to that protons in the nucleus. The electronic shell structure is responsible for the chemical properties of the atom.

equivalent dose**:** the absorbed dose delivered by a type of radiation averaged over a tissue or organ by means of radiation weighting factors, which are specific for each type of radiation. The unit of equivalent dose equals 1 J.kg$^{-1}$, and is called sievert (Sv).

Environment**:** the surroundings in which animals and plants live. The environment includes physical and chemical factors as well as living organisms. Living organisms are affected not only by the physical and chemical factors (temperature, waterquality, gases, light, pressure, chemical form of the substances), but also by biotic factors (food resources, competition with other species, predators and parasites) of their environment. The radioactivity levels in the environment may alter many of those factors.

fissile (atom)**:** an atom capable of undergoing fission through the bombardment of a thermal (slow) neutron.

fission (nuclear)**:** the process in which an atomic nucleus splits into two or more fragments (fission products) with the emission of neutrons. It is accompanied by the release of energy in the form of gamma rays and the kinetic energy of emitted particles manifested as heat. Fission occurs spontaneously in some nuclei, or can be induced by bombarding nuclei (such as those of $^{233}$U, $^{235}$U or $^{239}$Pu) with neutrons, as it is the case in nuclear reactors.

fission decay chain**:** a short radioactive series started with a fission fragment, involving the successive emission of electrons.

fission product**:** a radionuclide resulting from the fission of a fissile or fissionable nuclide.

fuel cycle (nuclear)**:** the series of steps involved in supplying fuel for nuclear power reactors. The nuclear fuel cycle starts with mining and milling of

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| | uranium, proceeds in processing plants to obtain nuclear fuel for reactors that after being used become spent fuel. The next step can either be storage or reprocessing the spent fuel to recover fissionable material to civil or military uses. Nuclear wastes are produced in all phases of the nuclear fuel cycle. |
| fusion reaction**:** | a nuclear reaction that brings together two lighter to form a heavier one overcoming their repulsion, and releasing high amounts of energy. The binding energy of the resulting element is higher than the lighter ones. |
| gamma rays**:** | High energy photons emitted during radioactive decay. |
| half-life**:** | The time elapsed for the radioactivity of a sample to decrease to half of its initial value. Thus, after two half-lives the radioactivity will be a quarter of its initial value, and so on. Half-lives range from a small fraction of a second to over ten billion years. The concept of half-life is intrinsically connected with exponential decay. |
| model**:** | A physical or mathematical representation of reality. |
| moderator**:** | A material such as water, graphite or heavy water used in a nuclear reactor to reduce the speed of fast neutrons to facilitate the fission of fissile atoms. |
| mass number (A)**:** | The numbers of protons and neutrons in the nucleus of an atom, each taken as a unit of mass. |
| neutron**:** | One of the three main subatomic particles (the others are the proton and the electron). Neutrons have about the same mass as protons, and occur in the nuclei of all atoms except hydrogen. They are highly penetrating, and are moderated (slowed down) by colliding with the nuclei of light atoms. In addition, neutrons induce certain heavy nuclei to undergo fission |
| nuclear chain**:** | A fission reaction maintained because neutrons released by the splitting of some nuclei proceed to split others, releasing more neutrons, in such a way that the reaction is maintained indefinitely. Also known as nuclear reaction chain. |
| photon**:** | The quantum of electromagnetic radiation energy. |
| primary coolant**:** | The liquid or gas that flows over the reactor core, removing heat generated during the fission process. |
| projected dose**:** | The dose to be received if no protective or remedial action is taken. |
| proton**:** | An elementary particle found in the nucleus of all atoms. The proton has a positive electric charge equal in magnitude to that of the electron. |
| quantum**:** | The general term for the indivisible unit of any form of energy, referring in particular to the photon. |
| radiation dose**:** | a general term that is used to describe the quantity of energy absorbed per unit mass of tissue or material. |
| Radioactivity**:** | The spontaneous disintegration of certain stable nuclei, accompanied by the emission of alpha particles, beta rays or gamma rays. All isotopes of atomic masses greater than 210 are radioactive. |

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| neutron**:** | an uncharged subatomic particle with rest mass slightly larger than that of the proton. Although a free neutron is unstable, with a half-life of 12 min, neutrons bound within the nucleus of an atom are stable. All nuclei apart from hydrogen contain neutrons, which contribute to the nuclear cohesive forces and separate the mutually repulsive protons. Free neutrons are produced in many nuclear reactions, including nuclear fission. |
| proton**:** | a positively charged subatomic particle, which is a fundamental constituent of any atomic nucleus. Its mass is approximately 1,836 times that of the electron. A proton carries a unit positive charge equal to the negative charge of an electron. |
| plutonium**:** | The common name of the isotope $^{239}$Pu, a fissile material used in nuclear weapons. Plutonium is obtained through the capture of a neutron by $^{238}$U, resulting in the isotope $^{239}$U, which decays by beta emission to $^{239}$Np, the latter also decays by beta emission yielding $^{239}$Pu. Plutonium has Z = 94. |
| natural uranium**:** | The common name of the isotope $^{238}$U, because its natural abundance is 98.2%. The half-life of $^{238}$U is 4.5 billion years, which makes it the parent of the uranium decay series. The isotope $^{238}$U decays by alpha emission to $^{234}$Th. Uranium has Z = 92. |
| sievert (Sv)**:** | The SI unit for equivalent dose. 1 Sv equals 1 J.kg$^{-1}$. |

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**Biographical Sketch**

**Anselmo Salles Paschoa** was born in Rio de Janeiro, Brazil, on December 15, 1937. Mr Paschoa holds a PhD degree from New York University. He is a Full Professor at Pontifícia Universidade Católica do Rio

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