NUCLEAR ACTIVITIES: IONISING RADIATIONS AND HEALTH RISKS

CHAPTER 1

Nuclear activities are defined by the Public Health Code as "activities involving a risk of human exposure to ionising radiations, emanating either from an artificial source – whether a material or device – or from a natural source when natural radionuclides are or have been processed for their fissile or fertile radioactive properties, as well as interventions designed to prevent or mitigate a radiological risk following an accident or contamination of the environment". These nuclear activities include those conducted in basic nuclear installations (BNIs) and during transport of radioactive materials, as well as in all industrial and research facilities and hospitals where ionising radiations are used.

The common goal of nuclear safety and radiation protection is to protect people and property against hazards, detrimental effects or problems of whatever nature, arising from the operation of nuclear or radiological facilities, the transport, use and transformation of radioactive or fissile materials, and exposure to naturally-occurring radiation.

Nuclear safety is defined as encompassing all technical and organisational provisions relating to the design, construction, operation, shutdown and dismantling of facilities comprising a source of ionising radiations, as well as those relating to the transport of radioactive materials, and intended to prevent accidents and mitigate any consequences thereof.

Radiation protection is defined as the set of prevention and monitoring rules, procedures and means aimed at preventing or minimising the harmful effects of ionising radiations on individuals directly or indirectly exposed, including through environmental contamination.

The Nuclear Safety Authority (ASN), created by Nuclear Transparency and Security Act 2006-686 of 13 June 2006, is responsible for the regulation of nuclear safety and radiation protection in all fields using sources of ionising radiations or involving transport of radioactive materials. With regard to radiation protection, other organisations such as the conventional safety inspectorate, the inspectorate for installations classified on environmental protection grounds and the medical devices inspectorate also have specific regulatory roles.

1 HAZARDS AND RISKS OF IONISING RADIATIONS

1 | 1 Biological and health effects

Whether it consists of charged particles, for example an electron (beta radiation) or a helium nucleus (alpha radiation), or of electromagnetic radiation photons (X rays or gamma rays), ionising radiations interact with the atoms and molecules making up the cells of living matter and alters them chemically. Of the resulting damage, the most significant concerns the DNA of the cells and is not fundamentally different from that caused by certain toxic chemical materials.

When not repaired by the cells themselves, this damage can lead to cell death and the appearance of health effects once tissues are no longer able to carry out their functions.

These effects, called "deterministic effects", have been known for a long time, as the first effects were observed with the discovery of X rays by Roentgen. They become apparent once the quantity of radiation absorbed exceeds a certain dose level, depending on the type of tissue exposed; the effects increase proportionally to the dose of radiation received by the tissue.

Cells can also repair the damage thus caused, although imperfectly or incorrectly.

Of the damage that persists, that to the DNA is of a particular type, because residual genetic anomalies can be transmitted by successive cellular division to new cells. A genetic mutation is still far removed from transformation into a cancerous cell, but the damage due to ionising radiations may be a first step towards cancerisation.

The suspicion of a causal link between the occurrence of cancer and exposure to ionising radiations dates from the beginning of the 20th century (observation of skin cancer on radiodermatitis).

Since then, several types of cancers have been observed in occupational situations, including leukaemias, primitive broncho-pulmonary cancers owing to radon inhalation and bone sarcomas. In addition to the study of occupational cancers, the monitoring of a cohort of about 85,000 people irradiated in Hiroshima and Nagasaki shed light on induced cancers and the resulting mortality, following exposure to ionising radiations. Other epidemiological work, in particular in radiotherapy, highlighted a statistically significant rise in secondary cancers among patients treated using radiotherapy and attributable to ionising

Child leukaemia

After the publication of a German study on the occurrence of leukaemia in children living near nuclear power plants at the end of 2007 and the IRSN summary of the epidemiological studies already published on this subject, ASN set up a working group at the end of 2008 to assess the available knowledge on the risk of leukaemia in children living in the vicinity of basic nuclear installations. Based on an inventory of the possible causes of child leukaemia, the group is also tasked with proposing the studies and research necessary for improving currently available knowledge. The pluralistic group is a combination of scientific experts, from the fields of medicine, epidemiology and radiation protection in particular, and personalities whose personal experience will enable them to make a valuable contribution to the debate. Foreign experts and personalities will also be participating.

radiations. We should also mention the Chernobyl accident which, as a result of the radioactive iodines released, caused a peak in the incidence of thyroid cancers in children in the areas near the accident.

The occurrence of carcinogenic effects is not linked to a dose threshold and only a probability of occurrence can be stated for any given individual. This is the case with occurrence of radiation-induced cancers. We then talk of probabilistic, stochastic or random effects.

Cover of a cancer register (InVS) – Publication 2003

The internationally established health goals of radiation protection aim to avoid the appearance of deterministic effects, but also to reduce the probability of radiation-induced cancers appearing.

1 | 2 Evaluation of ionising radiations risks

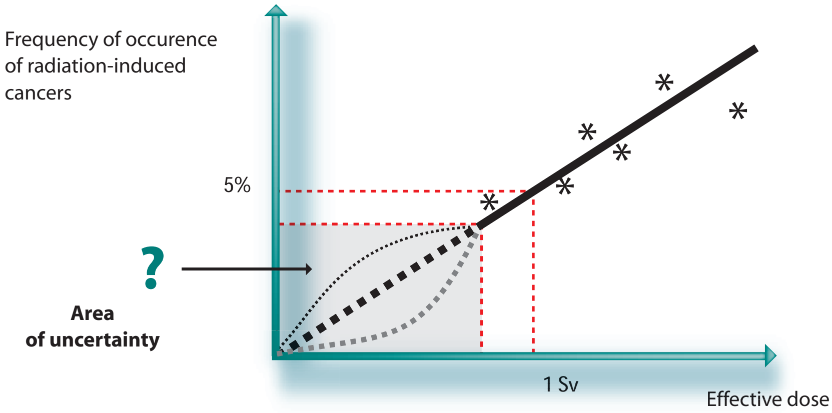
Cancer surveillance is organised on the basis of *département*[1] registers (10 registers covering 11 *départements* or about 15% of the general population) and specialised registers (12 specialised registers, including 2 national registers for cancers in children under 15 years old, concerning haematological malignancy and solid tumours in children).

As with any monitoring system, the aim is to highlight spatial differences in incidence in the areas covered, to identify trends in terms of increased or reduced incidence in the various cancer locations over time, or to locate a cluster of cases in one of the areas covered. This intentionally descriptive monitoring method cannot identify radiation-induced cancers, as their form is not specific to ionising radiations.

Epidemiological investigation supplements monitoring. The purpose of epidemiological surveys is to highlight an association between a risk factor and the occurrence of a disease, between a possible cause and an effect, or at least to enable such a causal relation to be postulated with a very high degree of probability. However, one should not ignore the difficulty in conducting these surveys or arriving at convincing conclusions when the latency of the

1. *département:* Administrative region headed by a *Préfet*

Diagram 1: linear "dose-effects" relationship (without threshold)



disease is long or when the number of expected cases is small, which are both characteristics of exposure to ionising radiations of less than 100 mSv. The epidemiological surveys were thus only able to link pathologies to ionising radiations for relatively high radiation doses at high dose rates (for example: monitoring of the populations exposed to the Hiroshima and Nagasaki bombings).

With a view to risk management, use is then made of the risk evaluation technique which uses calculations to extrapolate the risks observed at higher doses in order to estimate the risks incurred during exposure to low doses of ionising radiations. Internationally, this estimate uses the conservative scenario of a linear relationship without threshold between exposure and the number of deaths through cancer. Thus an estimate of the number of cancers attributable to exposure to ionising radiations can be calculated, using a linear extrapolation without threshold of the relationship observed at high doses. The legitimacy of these estimates however remains open to debate within the scientific community.

On the basis of the scientific work of UNSCEAR, the International Commission on Radiological Protection (see publication ICRP 103) published risk coefficients for death through cancer due to ionising radiations, showing a 4.1% excess risk per sievert for workers and 5.5% per sievert for the general population. Use of this model, for example, would lead to an estimate of about 7,000 deaths in France every year, as a result of cancer due to naturally-occurring radiation.

Evaluation of the risk of lung cancer due to radon is the subject of a specific model, based on observation of epidemiological data concerning mine workers. Assuming a linear relationship without threshold for low-dose

UNSCEAR

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) was set up in 1955 during the 10th session of the General Assembly of the United Nations. It comprises representatives from 21 countries and reports to the General Assembly of the United Nations. It is a scientific organisation whose aim is to validate and approve the results of national or international studies into the effects of ionising radiations on man.

In August 2008, UNSCEAR published a first report on the epidemiology of radiation-induced cancers, cardiovascular diseases and diseases other than cancers caused by radiation. A second volume concerning the non-targeted and delayed effects of ionising radiations and its effects on the immune system, along with a review of source-effect relationships for radon in the home and radon in a professional setting, was expected for late 2008.

exposure, the relative risk linked to radon exposure, for a radon concentration of 230 Bq/m3, would be about the same as passive smoking (USA Academy of Science, 1999).

The health goal of reducing the risk of cancer linked to ionising radiations cannot be directly observed through epidemiology; the risk can be calculated if we assume the existence of a linear relationship without threshold between exposure and the risk of death from cancer.

1 | 3 Scientific uncertainty and vigilance

The action taken in the fields of nuclear safety and radiation protection in order to prevent accidents and limit detrimental effects has led to a reduction in risks but has not reached either zero risk or zero impact, whether in terms of the doses received by medical or industrial workers, or those associated with discharges from BNIs. However, many uncertainties and unknown factors persist and require ASN to remain attentive to the results of the scientific work in progress, for example in radiobiology and radiopathology, with possible spin-offs for radiation protection, particularly with regard to management of risks at low doses.

We could for instance mention several examples of areas of uncertainty concerning high dose radiation-induced pathologies, the effects of low doses and environmental protection:

• *High dose radiation-induced pathologies*

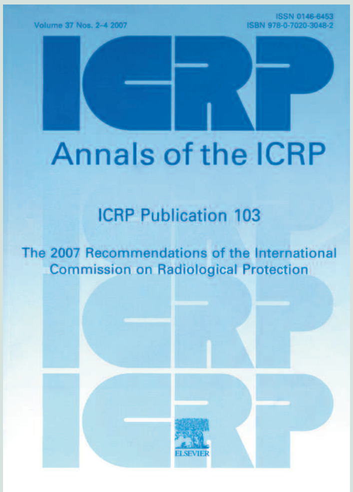
The treatment of serious damage due to overexposure to ionising radiations - The treatment of this serious damage from over-exposure is extremely difficult and indeed disappointing, because they are persistent and evolve over a period of time. 2006 was marked by two exceptional success stories concerning two victims of an accident involving external irradiation from an industrial gammagraph source on the one hand and an ionisation source on the other. The therapeutic innovations developed by IRSN (French Institute for Radiation Protection and Nuclear Safety) and the Percy armed forces hospital (HIA) in Clamart consist in using specific cytokines to stimulate targeted cell lines, as well as autologous mesenchymal stem cells cultivated in vitro and grafted to allow the renewal of the damaged tissue. These innovative treatments were in 2007 the subject of a clinical research protocol, headed by the Saint Antoine Hospital (Paris), for treating serious radiotherapy damage observed in the patients involved in the Epinal accident. The radiotherapy events notified to ASN in 2007 clearly raise the question of a scientific watching brief in the treatment of the secondary

ICPR publication 103

The International Commission on Radiological Protection (ICRP) has for a number of decades now been issuing radiation protection recommendations, which generally constitute the basis for international standards (in particular those issued by the IAEA) and EU directives.

The optimisation principle is the core feature of the new recommendations published at the end of 2007 (ICRP 103), although the principles of justification and limitation are maintained. Whatever the type of exposure situation (scheduled exposure, emergency exposure or existing exposure), the ICRP recommends reducing individual doses to a level as low as is reasonably achievable. For correct implementation of the principle of optimisation, the ICRP proposes establishing reference dose values for each exposure situation. The individual dose limits, applicable to exposure arising from all sources to which the individual is exposed, remain unchanged. Finally, the exposure categories (at work, the public and medical applications) are also maintained.

The ICRP thus updated the existing system (ICRP 60), without radically altering it, in order to take account of the need for stability expressed by both professionals and regulatory authorities.



The recommendations of ICRP 103 – December 2007 effects of irradiation, including non-accidental, in particular in radiotherapy where their frequency is about 5% (no doubt partly due to the high individual radio-sensitivity of the patients).

Hyper-sensitivity to ionising radiations - The effects of ionising radiations on personal health vary from one individual to the next. We have for example known for a long time that the same dose does not have the same effect on a growing child as on an adult, and this has been incorporated into the regulations. However, in addition to these well-known disparities, certain individuals could be hyper-sensitive to radiation owing to deficiencies in their cellular repair mechanisms controlled by the genetic machinery: in any case this is what is indicated by the in vivo observations made by radiotherapists and the in vitro observations made by biologists. Delicate ethical questions then legitimately arise, clearly going beyond the framework of radiation protection: for example should one search for the possible hyper-sensitivity of a worker likely to be exposed to ionising radiations? Should the general regulations, for example, provide for specific protection for those concerned by hyper-sensitivity to ionising radiations?

• *Effects of low doses*

The linear relationship without threshold - This assumption, adopted to model the effects of low doses on health (see point 1|2), albeit practical from the regulatory standpoint, and albeit conservative from the health standpoint, is not as scientifically well-grounded as might be hoped for: there are those who feel that the effects of low doses could be higher, while others believe that these doses could have no effect below a certain threshold, with some even postulating that low doses could have a beneficial effect! Research into molecular and cellular biology is leading to progress, as are epidemiological surveys of large groups. But faced with the complexity of the DNA repair and mutation phenomena, and faced with the limitations of the methods used in epidemiology, the uncertainties remain and precaution is essential for the authorities.

Dose, dose rate and chronic contamination - The epidemiological surveys performed on individuals exposed to the Hiroshima and Nagasaki bombings, have given a clearer picture of the effects of radiation on health, for high-dose and high dose rate external exposure. The studies begun in the countries most affected by the Chernobyl accident, Belarus, Ukraine and Russia, could also advance current knowledge of the effects of radiation on human health, for lower dose and lower dose rate internal exposure levels, as well as of the consequences of chronic exposure to ionising radiations (by external exposure and contamination through food) owing to the long-term contamination of the environment.

Hereditary effects - The appearance of possible hereditary effects from ionising radiations in man remains uncertain. Such effects have not been observed among the survivors of the Hiroshima and Nagasaki bombings. However, hereditary effects are well documented in experimental work on animals: the mutations induced by ionising radiations in the embryonic germ cells can be transmitted to the descendents. The recessive mutation of an allele will remain invisible as long as the allele carried by the other chromosome is not affected. Although it cannot be absolutely ruled out, the probability of this type of event nonetheless remains low.

• *Environment*

Protection of non-human species – The purpose of radiation protection is to prevent or mitigate the harmful effects of ionising radiations on individuals directly or indirectly exposed, including through environmental contamination: human protection involves environmental protection, as illustrated by the impact assessments submitted to the public inquiries held to authorise BNI discharges. But quite apart from this environmental protection aimed at protecting present and future generations of mankind, one could also envisage the protection of nature, in the specific interests of animal species or the rights of nature. On this subject, even more so than those mentioned earlier, defining an acceptable level will be a delicate business. ASN will therefore closely monitor the work being done on this subject by ICRP, the results of which could have important repercussions in the regulatory field.

2 FIELDS OF ACTIVITY INVOLVING RADIOLOGICAL RISKS

The activities involving a risk of exposure to ionising radiations can be grouped into the following categories:

– basic nuclear installations;

– transport of radioactive and fissile material for civil use;

– small-scale nuclear activities;

– contaminated sites;

– activities enhancing naturally occurring ionising radiations.

2 | 1 Basic nuclear installations

2 | 1 | 1 Definition

The regulations classify nuclear facilities in various categories corresponding to procedures of various stringency, depending on the scale of the potential hazards. The main fixed nuclear installations, known as "basic nuclear installations" (BNIs), are defined in Article 28 of the Nuclear Transparency and Security Act 2006-686 of 13 June 2006. Decree 2007-830 of 11 May 2007 concerning the list of basic nuclear installations, gives a more precise definition of BNI categories:

– nuclear reactors, with the exception of those equipping a means of transport;

– particle accelerators;

– plants for the separation, manufacture or transformation of radioactive materials, in particular nuclear fuel manufacturing plants, spent fuel reprocessing plants or radioactive waste packaging plants;

– facilities designed for the disposal, storage or use of radioactive materials, including waste.

The last three types of facilities are however only covered by BNI regulations when the total quantity or activity level of the radioactive materials exceeds a threshold set, according to the type of facility and the radionuclide concerned, by a joint order of the ministers for the Environment, Industry and Health.

Nuclear facilities which are not considered to be BNIs may be subject to the provisions of book V of the Environment Code (conditions applicable to installations classified on environmental protection grounds (ICPEs).

The BNI status as at 31 December 2008 is given in appendix A.

2 | 1 | 2 Safety of basic nuclear installations

The fundamental principle underpinning the organisational system and the specific regulations applicable to nuclear safety is that the licensee is responsible for safety. The public authorities ensure that this responsibility is fully assumed, in compliance with the regulatory requirements.

The respective roles of the public authorities and the licensee can be summarised as follows:
– the public authorities define the general safety objectives;
– the licensee proposes technical procedures for attaining them, and justifies them;
– the public authorities ensure that these procedures are consistent with the goals set;
– the licensee implements the approved measures;
– during their inspections, the public authorities check correct implementation of these measures and draw the corresponding conclusions.

2 | 1 | 3 Radiation protection in the basic nuclear installations

BNIs are “nuclear activities”, as defined by the Public Health Code, but are subject to specific regulation and supervision, owing to the significant risks of exposure to ionising radiations.

The licensee is required to take all necessary steps to protect the workers against the hazards of ionising radiations, and more particularly to follow the same general rules as those applicable to all workers exposed to ionising radiations (annual dose limits, categories of exposed workers,

Ten yearly outage performed by the ASN Strasbourg division in the Cattenom nuclear power plant (Moselle *département*) on 23 June 2008

The impact of tritium: ASN's forward-looking approach

Tritium is a radioactive isotope of hydrogen and is to be found in the environment in three forms: a liquid form (tritiated water or HTC), a gaseous form known as HT and an organic form called OBT. Tritium occurs naturally in the environment as a result of the effect of cosmic radiation on nitrogen atoms and is also one of the main radionuclides emitted by nuclear reactors, spent nuclear fuel reprocessing installations, industries and laboratories using this radionuclide and waste management facilities.

Medical authorities in France and abroad, as well as the international health organisations, agree that the radiotoxicity of tritium is low. It has also been accepted that it does not build up in the food chain (no bioaccumulation).

However, recent observations could lead to a review of this opinion: measurements taken in the United Kingdom (Rife reports) showed higher than expected levels of tritium in fish and shellfish. At the same time, studies into the biokinetics of tritium (modelling of the behaviour of tritium in living organisms) could also lead to a reassessment of the parameters used in characterising its radiotoxicity.

As a result of the questions raised by this work, ASN wished to obtain a precise analysis of the existing studies on the subject and at the beginning of 2008, it therefore decided to set up two independent working groups, comprising scientists, licensees and associations:
- *a "tritium impact" group, responsible for producing an inventory of current scientific knowledge on the health impacts of tritium and the real scientific data on the bioaccumulative effect of tritium;*
- *a "defence in depth" group responsible for anticipating changes in discharges resulting from the use of new fuel management programmes and the construction of new installations (EPR and Iter), for examining technical possibilities concerning tritium treatment and for producing an inventory of current knowledge on its environmental impact.*

Each of these two working groups met twice in 2008 and their work will continue in 2009. ASN expects these working groups to produce an inventory of current knowledge and possibly recommendations by the end of 2009. The conclusions of this work will be published by ASN.

definition of supervised areas and controlled areas, etc.), along with the technical and administrative requirements specific to BNIs (organisation of work, prevention of accidents, keeping of registers, medical monitoring of workers from outside contractors, etc.). The licensee must also take the steps necessary to attain and maintain an optimum level of protection of the population, in particular by checking the effectiveness of the technical systems implemented for this purpose.

2 | 1 | 4 Environmental impact of basic nuclear installations

Under normal operating conditions, nuclear facilities discharge liquid and gaseous effluents, which may or may not be radioactive. The environmental and health impact of these discharges must be strictly limited.

The facilities must therefore be designed, operated and maintained in such a way as to limit the production of such effluents. They must be treated so that the corresponding discharges are kept to a level as low as reasonably achievable. These discharges may not exceed the limit values set on a case by case basis by the public authorities, using the best technologies available at an economically acceptable cost, and taking into account the particular characteristics of the site. Finally, these discharges must be measured and their actual impact regularly evaluated, in particular with regard to radioactive discharges.

2 | 1 | 5 Disposal of radioactive waste

Like all industrial activities, nuclear activities generate waste. Some of this waste is radioactive. The three fundamental principles on which strict radioactive waste management is based, are the responsibility of the waste producer, the traceability of the waste and public information. For very low level waste (VLL), application of a management system based on these principles, if it is to be completely efficient, rules out setting a universal threshold below which regulation can be dispensed with.

Spectrometry measurement of medical waste at Nantes university hospital (Loire-Atlantique) – September 2007

Package of radioactive materials inspected by ASN at Roissy Charles-de-Gaulle Airport – April 2006

The technical management provisions to be implemented must be tailored to the hazard presented by the radioactive waste. This hazard can be mainly assessed through two parameters: the activity level, which contributes to the toxicity of the waste, and the lifetime defined by the half-life, the time after which the activity level is halved.

Finally, management of radioactive waste must be determined prior to any creation of new activities or modification of existing activities in order to:

– optimise the waste disposal routes;
– ensure control of the processing channels for the various categories of waste likely to be produced, from the front-end phase (production of waste and packaging) to the back-end phase (storage, transport, disposal).

2 | 2 Transport of radioactive and fissile material for civilian uses

When transporting radioactive or fissile materials, the main risks are those of internal or external exposure, criticality, or chemical hazard. Safe transport of radioactive materials relies on an approach called defence in depth:

– the package, consisting of the container and its content, is the first line of defence. It plays a vital role and must be able to withstand all foreseeable transport conditions;
– the transport means and its reliability constitute the second line of defence;
– finally, the third line of defence consists of the response resources implemented to deal with an incident or accident.

The consignor is responsible for implementing these lines of defence.

2 | 3 Small-scale nuclear activities

Ionising radiations, whether generated by radionuclides or by electrical equipment (X-rays), are used in very many areas of medicine (radiology, radiotherapy, nuclear medicine), human biology, research, industry, but also for veterinary and forensic applications as well as for conservation of foodstuffs.

In terms of radiation protection, most of these activities, which are also considered to be nuclear activities, are covered by the licensing or notification procedures stipulated in the Public Health Code or, as applicable, by particular procedures (case of ICPEs) in which, on the basis of information forwarded by the licensee, the various aspects relating to radiation protection are examined, both with regard to the protection of workers and that of the population in general. Protection is also taken into account through the requirements applied to discharges of liquid and gaseous effluents. In the case of use for medical purposes, patient protection issues are also reviewed.

For activities other than ICPEs, authorisations are issued to the persons in charge of using the ionising radiations. The fact that the responsibility is targeted on the user in no way means that the head of the company is relieved of his duty to provide the person in possession of the sources with all resources necessary for radiation protection, be they human (person with competence for radiation protection, medical radiation physics expert), technical (premises and equipment conforming to current standards), organisational, or related to measurements (dosimetry and measuring instruments). Some activities (e.g.: medical or dental radiology facilities) are simply subject to notification.

If they use unsealed radioactive sources, then small-scale nuclear activities also generate radioactive waste, which

Examples of uses of ionising radiation in industry and research

Gammagraph inspection preparation

Dose rate check using a babyline at the CHU Henri Mondor University hospital in Créteil – August 2008

has to be managed in accordance with the principles described in point 2|2|5.

2|4 Contaminated sites

Management of sites contaminated by residual radioactivity resulting either from a past nuclear activity, or an activity which generated deposits of natural radionuclides, warrants specific radiation protection actions, in particular if rehabilitation is envisaged.

In the light of the current or future uses of the site, decontamination targets must be set and disposal of the waste produced during clean-up of the premises and the contaminated soils must be controlled, from the site up to the storage or disposal location.

2|5 Activities enhancing naturally occurring ionising radiations

Exposure to naturally occurring ionising radiations, when enhanced by human activities (TENORM), justifies monitoring and even risk evaluation and management, if likely to generate a risk for exposed workers and, as applicable, the population in general.

Certain professional activities which are not covered by the definition of "nuclear activities" can thus significantly increase exposure to ionising radiations on the part of the workers and, to a lesser extent, the populations living in the vicinity of the places where these activities are carried out, in the event of discharge of effluents or disposal of low-level radioactive waste. This is in particular the case with activities using raw materials, construction materials or industrial residues containing natural radionuclides which are not used for their fissile or fertile radioactive properties.

The natural families of uranium and thorium are the main radionuclides found. Among the industries concerned, we could mention the phosphate mining and phosphated fertiliser manufacturing industries, the dyes industries, in particular those using titanium oxide and those using rare earth ores such as monazite.

The radiation protection actions required in this field are based on precise identification of the activities, estimation of the impact of the exposure on the individuals concerned, taking corrective action to reduce this exposure if necessary, and monitoring.

This is in particular the case with activities which use materials (raw materials, construction materials, industrial residues) containing natural radionuclides not used for their radioactive, fissile or fertile properties. The natural families of uranium and thorium are the main radionuclides encountered. Among the industries concerned, we could mention the phosphate mining and phosphated fertiliser manufacturing industries, the dyes industries, in particular those using titanium oxide and those using rare earth ores such as monazite.

Since August 2008, this monitoring has been extended to the partner workplaces located in priority geographical areas. Finally the exposure of aircrews to cosmic radiation, aggravated by prolonged periods at altitude, also warrants dosimetric monitoring.

3 EXPOSURES TO IONISING RADIATIONS

The pathology monitoring systems set up (cancer registers for example) do not enable those pathologies attributable to ionising radiations to be determined. Nor do we have reliable and easily measurable biological indicators which could be easily used to recreate the radiation dose to which the individuals were exposed. In this context, “risk monitoring” is performed by measuring ambient radioactivity indicators, or at best by measuring the dose rates linked to external exposure to ionising radiations or internal contamination, or failing which, by measuring values (concentration of radionuclides in radioactive waste discharges) which would then enable an estimate of the doses received by the exposed populations to be calculated.

The entire French population is potentially exposed, although to different extents throughout the country, to ionising radiations of natural origin and to radiation created by human activities. The average exposure of the French population is estimated, per inhabitant, at 3.3 mSv per year, but this exposure is subject to wide individual variability, in particular depending on the place of residence and the number of radiological examinations received (source: IRSN 2006). Depending on the location, the average individual effective dose can vary by a factor of 2 to 5. The following diagram represents an estimate of the respective contributions of the various sources of French population exposure to ionising radiations.

These data are however still too imprecise to allow identification of the most exposed categories or groups of individuals for each exposure source category.

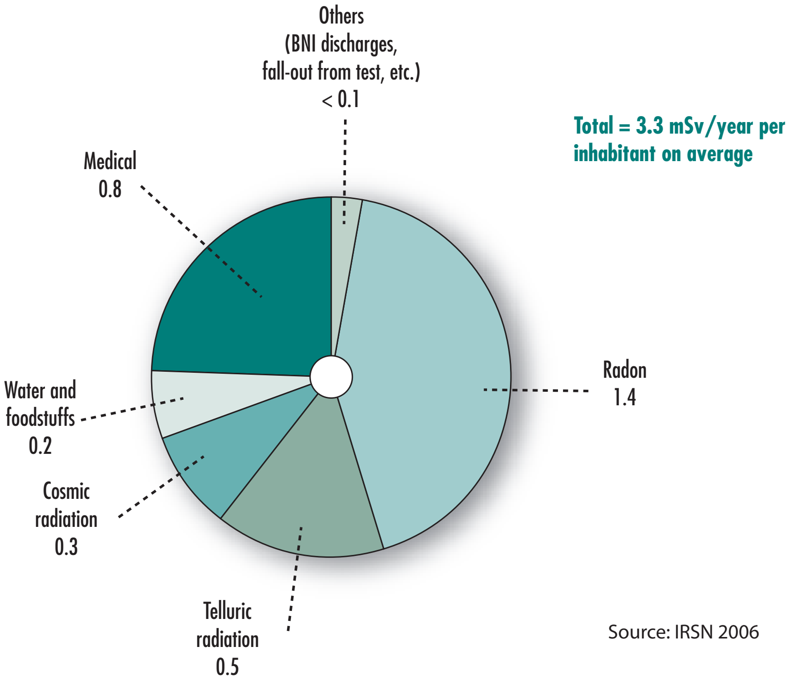
3 | 1 Exposures of the population to natural ionising radiations sources

People have always been exposed to naturally occurring ionising radioactive materials (NORM) owing to the presence of radionuclides of terrestrial origin in the environment, radon emanations from the ground and exposure to cosmic radiation.

Terrestrial radiation (excluding radon)

Natural radionuclides of terrestrial origin are present at various levels in all aspects of our environment, including inside the human organism. They lead to external exposure of the population owing to gamma radiation emissions produced by the uranium 238 and thorium 232 chains and by the potassium 40 present in the soil, but also to internal exposure by inhalation of radon or

Graph 1: sources of exposure to radiation for the French population (annual averages)



Source: IRSN 2006

particles in suspension, and by ingestion of foodstuffs or drinking water.

The levels of natural radionuclides in the ground are extremely variable. The highest external exposure dose rates in the open air in France, depending on the regions, range between a few $nSv.h^{-1}$ and 100 $nSv.h^{-1}$.

The dose rate values inside residential premises are generally higher owing to the contribution of construction materials (an average of about an extra 20%).

Based on scenarios covering the time individuals spend inside and outside residential premises (90% and 10% respectively), the average annual effective dose due to external exposure to gamma radiation of terrestrial origin is estimated at about 0.47 mSv (IRSN 2006), as compared with the worldwide average of 0.46 mSv, estimated by UNSCEAR (2000).

The internal exposure through inhalation, owing to air suspension of particles of soil, is estimated at 0.002 mSv per year, while that due to the long-lived descendents of radon is estimated at about 0.01 mSv per year.

Health checks on the radiological quality of drinking water

The results of the health check on the radiological quality of drinking water, conducted by the DDASS in 2007, show that:

- *4.7% of the water samples analysed comprised an overall alpha activity level higher than the guideline value of 0.1 Bq/L;*
- *less than 0.1% of the water samples analysed comprised a residual overall beta activity higher than the guideline value of 1 Bq/L;*
- *no excess tritium activity level was observed;*
- *1.3% of the water samples analysed comprised a total indicative dose (TID) higher than 0.1 mSv/year (of which 0.13% had a TID higher than 0.3 mSv/year), a level as of which solutions to reduce exposure must be sought and the water is considered to be unsuitable for drinking and for preparation of food for infants, children and pregnant women (ASN recommendations, March 2007).*

The doses due to internal exposure of natural origin vary according to the quantities of radionuclides of the uranium and thorium families incorporated through the food chain, which depend on each individual's eating habits. According to UNSCEAR (2000), the average dose per individual is about 0.23 mSv per year. The average concentration of potassium 40 in the organism is about 55 Bq per kg, resulting in an average effective dose of about 0.18 mSv/per year.

Waters intended for human consumption, in particular groundwater and mineral waters, become charged in natural radionuclides owing to the nature of the geological strata in which they spend time. The concentration of descendants of uranium and thorium, but also of potassium 40, varies according to the département given the geological nature of the ground. For waters with high radioactivity, the annual effective dose resulting from daily consumption (2 litres/inhabitant/day) may reach several tens or several hundreds of µSv.

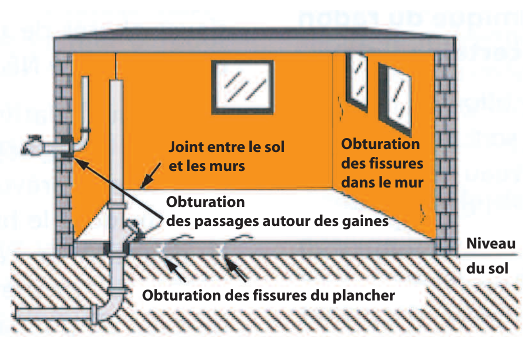
Exposure to radon

Exposure to radon in the home was estimated by measurement campaigns, followed by statistical interpretations (see IRSN atlas). The average radon activity value measured in France is 63 Bq/m^3, with about half the results being below 50 Bq/m^3, 9% above 200 Bq/m^3 and 2.3% above 400 Bq/m^3.

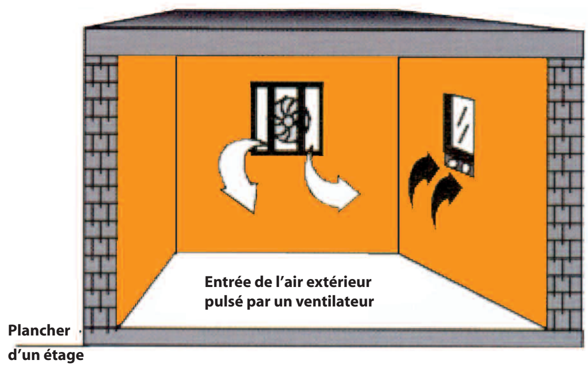
These measurements led to a classification of the départements according to the radon exhalation potential of the land (see chapter 3). For methodological reasons, the results of this supervision are still however too imprecise for an accurate assessment to be made of the doses linked

Residence exposed to radon

Sealing of radon entry channels
(sealing the ground)

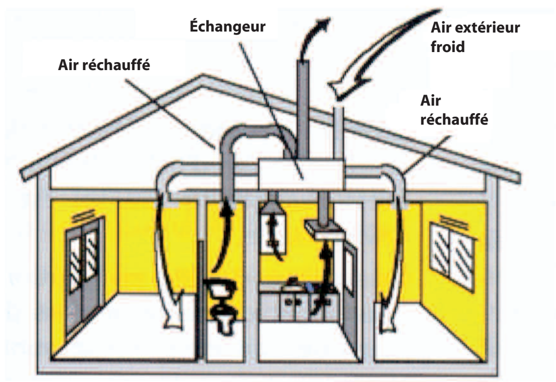


Pulsed air ventilation



Pas de conditions particulières sur les débits d'air

Reversible controlled mechanical ventilation
(with heat recovery)



Débit d'entrée d'air supérieur au débit de sortie d'air

Source: Building Industry Scientific and Technical Centre – CSTB

Table 1: results of radon measurement campaigns since 2005

Measurement campaign	Number of establishments checked	Establishments classified at less than 400 Bq/m³		Establishments classified between 400 Bq/m³ and 1000 Bq/m³		Establishments classified at higher than 1000 Bq/m³	
		Number	%	Number	%	Number	%
2005/2006	2,970	2,570	87	314	10	82	3
2006/2007	3,000	2,560	85	315	11	125	4
2007/2008	1,204	952	79	174	15	78	6

The percentages of the measurement results higher than the action levels (400 and 1000 Bq/m³) remain comparable from one year to the next. The smaller number of measurements taken during the latest campaign indicates that screening of the establishments, which began in 1999, is practically complete. As of 2009, a new screening cycle (10 years) will start.

to the actual exposure of the individuals. If we assume a home occupancy ratio of 90%, these values give an average annual dose of 1.4 mSv.

In premises open to the public, and in particular in teaching establishments and health and social care establishments, radon measurements have been taken since 1999.

Results of the measurement campaigns conducted since 2005 by organisations approved by ASN are presented in table 1.

External exposure due to cosmic radiation

Cosmic radiation is of two types, an ionic component and a neutronic component. At sea level, the ionic component is estimated at 32 nSv per hour and the neutronic component at 3.6 nSv per hour.

If we take account of the average time spent inside the home (which itself attenuates the ionic component of the cosmic radiation), the average individual effective dose in a locality at sea level in France is 0.27 mSv per year, whereas it could exceed 1.1 mSv per year in a mountain locality such as Cervières at 2,836 m altitude. The average annual effective dose per individual in France is 0.331 mSv per year. It is lower than the global average value of 0.38 mSv per year published by UNSCEAR.

3 | 2 Doses received by workers

3 | 2 | 1 Nuclear worker exposure

The system of monitoring external exposure of individuals working in facilities where ionising radiations are used has been in place for a number of decades. It is based on the mandatory wearing of personal dosimeters by workers likely to be exposed and is used to check compliance with the regulatory limits applicable to workers. The data recorded give the cumulative exposure dose over a given period (monthly or quarterly). They are fed into the SISERI information system managed by IRSN and are published annually. The SISERI system will also eventually allow collection of data supplied by "operational dosimetry", in other words, real-time measurement of external exposure doses and the dosimetric results of any internal contamination.

Results of dosimetry monitoring of worker external exposure to ionising radiations in 2007 (source: IRSN December 2008)

Total population monitored: 293,876 workers

Monitored population with a recorded dose below the detection threshold: 930,091, or about 78.3%

Monitored population with a recorded dose of between the detection threshold and 1 mSv: 51,797, or about 17.6%

Monitored population with a recorded dose of between 1 mSv and 20 mSv: 12,026, or about 4.1%

Monitored population which exceeded the annual effective dose of 20 mSv: 22 including 2 above 50 Sv

Collective dose (sum of individual doses): 56.83 Man.Sv

Annual average individual dose in the population which recorded a non-nil dose: 0.89 mSv

The results of dosimetric monitoring of worker external exposure in 2007 on the whole show that the prevention system introduced in facilities where sources of ionising radiations are used is effective, because for more than 95% of the population monitored, the annual dose remained lower than 1 mSv (effective annual dose limit for the public). However, these statistics do not reflect the whole picture, because in a few cases, the dosimeter exposure did not necessarily correspond to exposure of the worker (dosimeters not worn but exposed) and it is possible that some workers do occasionally fail to wear their dosimeters.

For each sector, tables 2 and 3 give the breakdown into the populations monitored, the collective dose and the number of times the annual limit of 20 mSv was exceeded. They clearly show a considerable disparity between doses according to the sector. For example, the medical and veterinary sector, which comprises a significant share of the population monitored (nearly 54%), only accounts for 19% of the collective dose; however, it does account for 18 annual limit overdoses (out of 22), including an overdose exceeding the 50 mSv level on two occasions.

The latest statistics published by IRSN in December 2008 show relative stability of the populations subject to dosimetric monitoring since 2000 (see diagrams 1 and 2). However, the collective dose, consisting of the sum of the individual doses, has been falling (about -50%) since 1996 at a time when the populations monitored have grown by about 20%. The optimisation approach implemented by the nuclear licensees during the 1990s is no doubt the explanation for this positive trend (see diagrams 3 and 4).

Table 2: BNI worker dosimetry, excluding defence (year 2007-source IRSN)

	Number of individuals monitored	Collective doses (Man.Sv)	Doses > 20 mSv
EDF	19,161	6	0
AREVA	9,055	2.37	0
CEA	6,192	0.22	0
IPN Orsay	2,656	0.12	0
Outside companies	15,808	11.85	0
Others	3,189	0.86	0

Table 3: dosimetry of workers in small-scale nuclear activities (year 2007-source IRSN)

	Number of individuals monitored	Collective doses (Man.Sv)	Doses > 20 mSv
Medicine	114,642	9.89	18
Dental	29,983	0.65	0
Veterinary	14,108	0.31	0
Industry	30,013	18.63	4
Research	4,607	0.54	0
Miscellaneous	33,940	4.03	0

The number of monitored workers whose annual dose exceeded 20 mSv has also been falling significantly (see diagram 5). Each overdose has to be the subject of a significant event notification by the nuclear activity licensee to ASN and of an individual investigation, jointly with the occupational physician and if necessary with the conventional safety inspectorate, in accordance with the circular of 16 November 2007 concerning coordination of the radiation protection inspectors and the conventional safety inspectors for the prevention of risks associated with ionising radiations.

3|2|2 Worker exposure to technologically-enhanced naturally occuring ionising radiations

There is no system for monitoring exposure of individuals working in activities which enhance exposure to NORM.

The studies so far published show that exposure can range from a few millisieverts to several tens of millisieverts per year.

Worker exposure to technologically-enhanced naturally occurring ionising radiations (TENORM) is the result

Diagram 1: evolution of the populations monitored, per field of activity, from 1996 to 2007 (source IRSN)

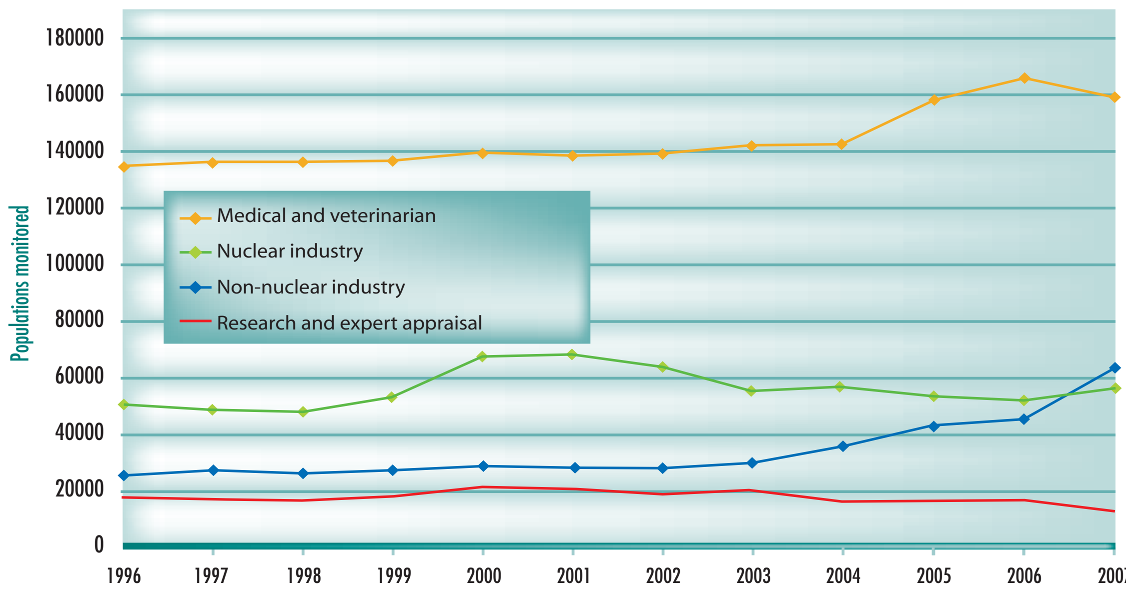


Diagram 2: evolution of the populations monitored and of collective doses, from 1996 to 2007 (source IRSN)

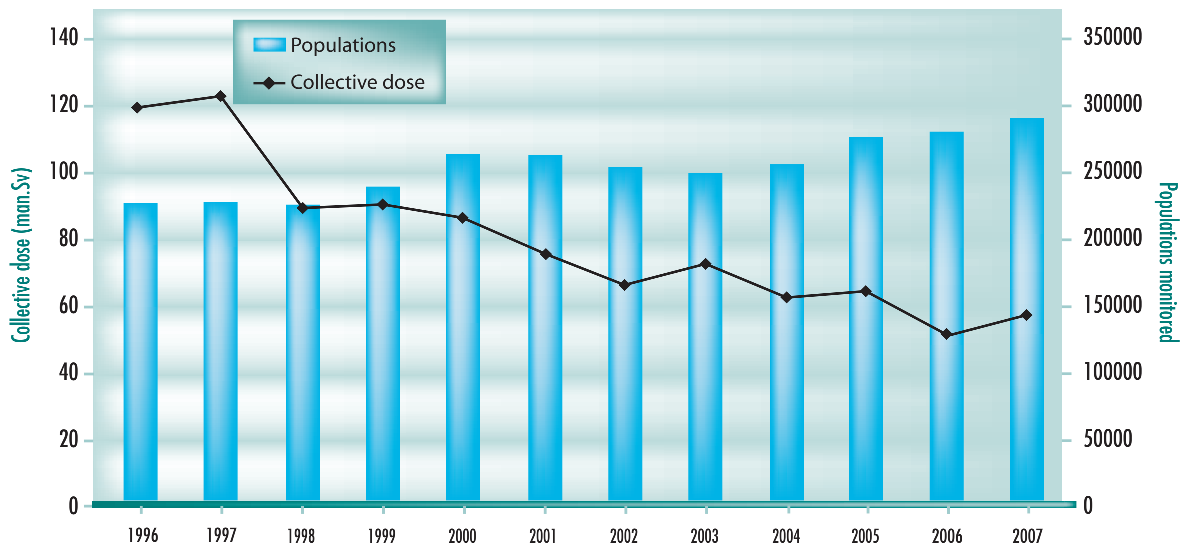


Diagram 3: evolution of collective doses, per field of activity, from 1996 to 2007 (source IRSN)

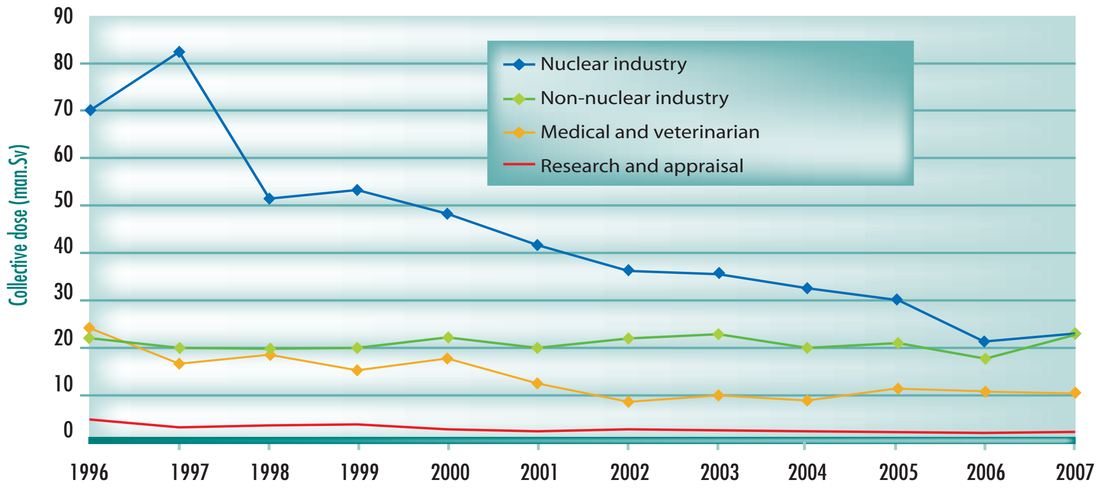


Diagram 4: evolution of number of workers monitored for whom the annual dose is higher than 20 mSv, from 1996 to 2007 (source IRSN)

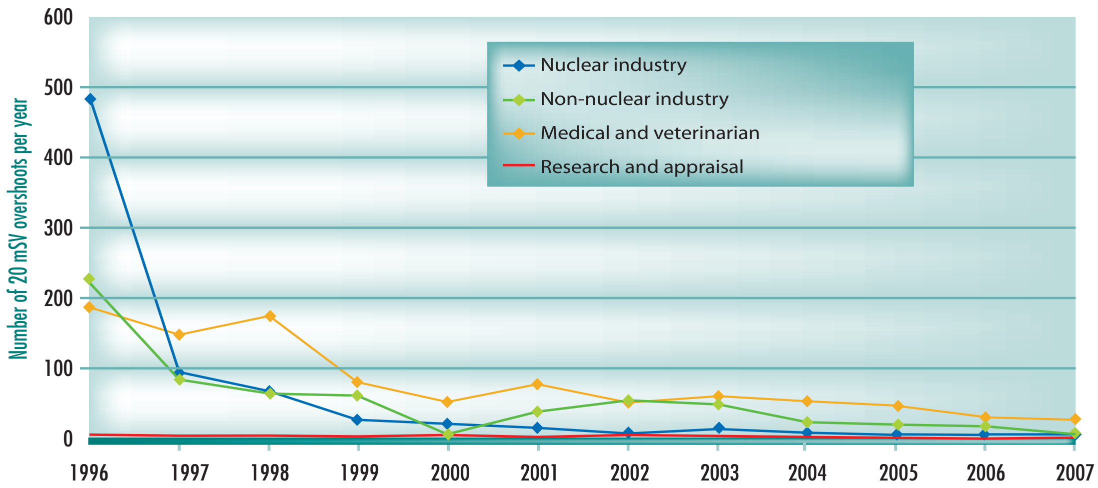
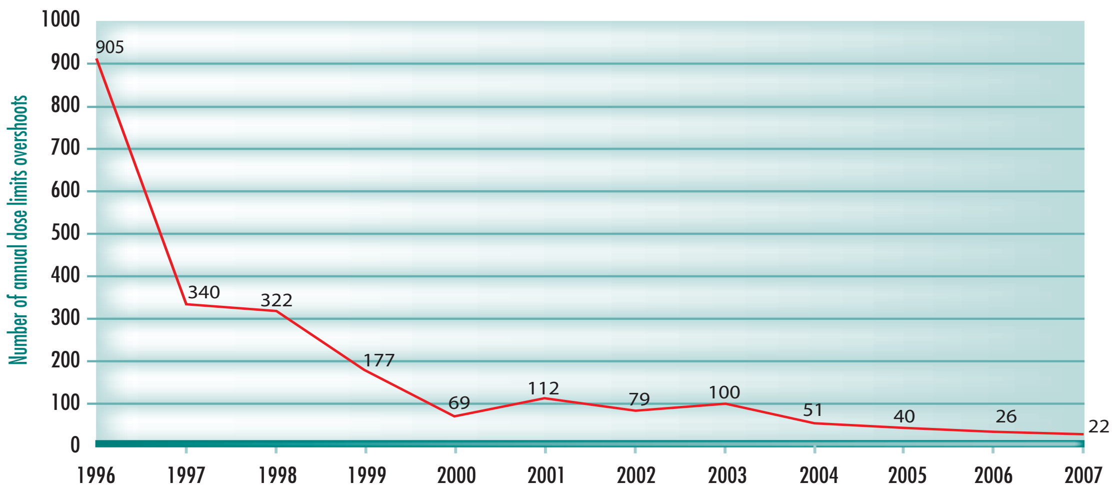


Diagram 5: evolution of number of workers monitored for whom the annual dose is higher than 20 mSv, from 1996 to 2007 (source IRSN)



either of the ingestion of dust containing large amounts of radionuclides (phosphates, metal ore), or of the inhalation of radon formed by uranium decay (poorly ventilated warehouses, thermal baths) or of external exposure due to process deposits (scale forming in piping for example). Thus, for example:

– industries handling raw materials that are naturally rich in radionuclides (phosphates, foundry ore, zirconium silicates, dye pigments, rare earths) can lead to annual worker exposure of several millisieverts;
– extraction of oil and natural gas can also lead to annual doses of several millisieverts through irradiation due to the particularly radionuclide-rich scale that forms in the pipelines;
– in spas, the high radon content of the water and the poor ventilation indicate that there would be significant doses, both for the personnel and the public coming to take the waters (a bibliographical study by IRSN of foreign spas shows that annual doses of 10 to 100 mSv are not uncommon for the personnel and from 1 to 4 mSv for the members of the public).

3 | 2 | 3 Flight crew exposure to cosmic radiation

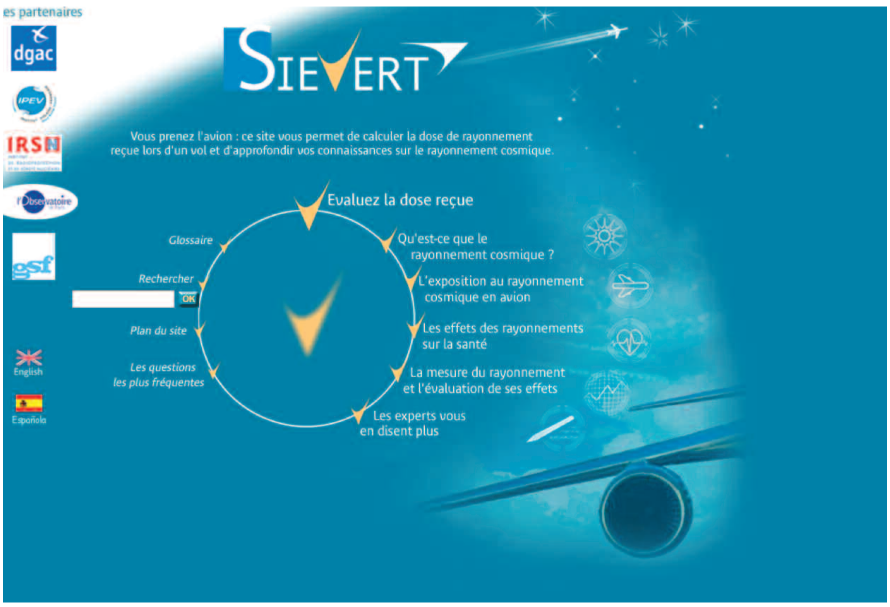
Airline flight crews and certain frequent travellers are exposed to significant doses owing to the altitude and the intensity of cosmic radiation at high altitude. These doses can exceed 1 mSv/year. We therefore estimate that the mean annual dose for "short-haul" crews would be from 1 to 2 mSv, from 3 to 5 mSv for "long-haul" crews and up to 10 mSv for certain air mail flight crews.

The observation system called SIEVERT, set up by the General Directorate for Civil Aviation, IRSN, the Paris Observatory and the Paul-Émile Victor French Institute for Polar Research (www.sievert-system.com), is used to estimate aircrew personnel exposure to cosmic radiation on the flights they make during the course of the year.

3 | 3 Doses received by the population as a result of nuclear activities

The automatic monitoring networks managed nationwide by IRSN (Téléray, Hydrotéléray and Téléhydro networks) offer real-time monitoring of environmental radioactivity and can highlight any abnormal variation. In the case of an accident or incident leading to the release of radioactive materials, these measurement networks would play an essential role by providing data to back the decisions to be made by the authorities and by notifying the population. In a normal situation, they take part in evaluating the impact of BNIs.

However, for methodological reasons, there is no overall monitoring system able to provide an exhaustive picture of the doses received by the population as a result of nuclear activities. Consequently, it is impossible to directly control compliance with the exposure limit for the population (see chapter 3). However, for basic nuclear installations, there is detailed accounting of radioactive effluent discharges and radiological monitoring of the environment is implemented around the installations. On the basis of the data collected, the dosimetric impact of these discharges on the populations in the immediate vicinity of the installations is



SIEVERT website: www.sievert-system.com/index.html then calculated using models for simulating transfers to the environment. The dosimetric impacts vary, according to the type of installation and the living habits of the reference groups chosen, from a few microsieverts to several tens of microsieverts per year.

These estimates are unknown for nuclear activities other than BNIs. Prior methodological studies are required in order to obtain a clear knowledge of these facilities, in particular the impact of discharges containing small quantities of artificial radionuclides originating from the use of unsealed radioactive sources in research or biological laboratories, or in nuclear medicine departments. For example, the impact of hospital discharges leads to doses of several microsieverts per year for the most exposed persons, in particular workers in the sewer networks (IRSN study 2005).

Situations inherited from the past, such as atmospheric nuclear tests and the Chernobyl accident can make a small contribution to exposure of the population. The average individual effective dose currently being received as a result of fall-out from the Chernobyl accident is estimated at between 0.010 mSv and 0.030 mSv/year (IRSN 2001). That due to the fall-out from atmospheric testing was in 1980 estimated at about 0.020 mSv. Given a decay factor of about 2 in 10 years, current doses are estimated at well below 0.010 mSv per year (IRSN 2006).

3 | 4 Doses received by patients

It is hard to accurately identify the overall exposure of medical origin, as we do not know the numbers of each type of examination practiced and the doses delivered for the same examination can vary widely. However, the national patient exposure observatory run by InVS and IRSN should benefit from the new social security classification of medical procedures and thus allow monitoring of a cohort of 600,000 patients treated by the private sector over the past 20 years. For the public sector, IRSN and InVS anticipate a similar survey in 2009, covering procedure breakdown, frequency and doses received.

However, global statistics (UNSCEAR 2000 report, volume 1, p. 401) drawn up for 1.53 billion inhabitants of the developed countries (1991-1996 data) indicate an annual effective dose rate per inhabitant of 1.2 mSv for radiology, 0.01 mSv for dentistry and 0.08 mSv for nuclear medicine. In Western Europe, for diagnostic radiological imaging, the annual effective dose per inhabitant in France

Groundwater samples from around the Gravelines nuclear power plant (Nord *département*) – September 2008

Table 5: Number of procedures, per sector, using ionising radiations

Type of procedure	Health institution	Private practice
Conventional radiology (including dental)	14.5 to 25 million	40.9 million
Scanner	2 to 3.8 million	2.2 million
Nuclear medicine	850,000	n/a *
Interventional radiology	892,000	n/a *
Total	61.3 to 73.6 million	

*n/a = not available

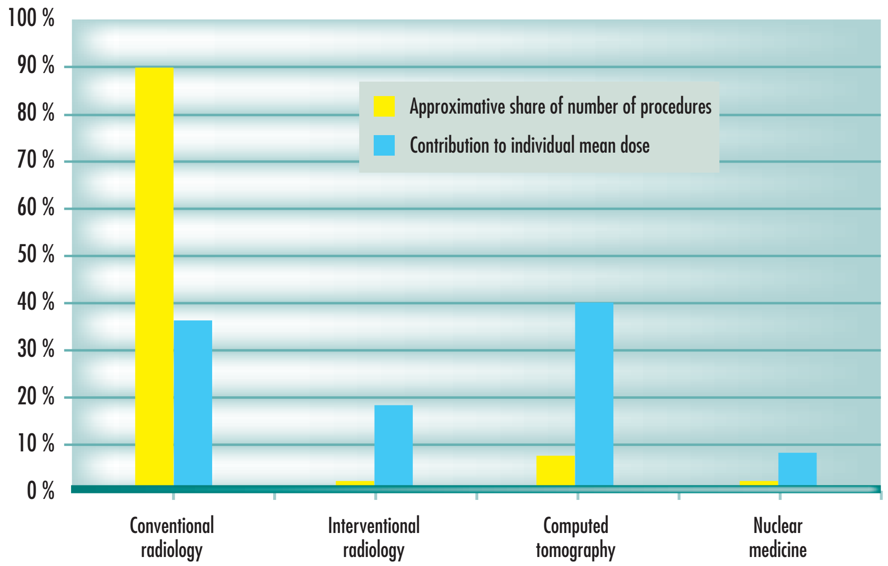
was assessed at 0.7/0.8 mSv, whereas it is 0.33 mSv for the United Kingdom and 1.9 mSv for Germany.

An inventory of medical exposure sites was drawn up in 2005 by IRSN and InVS, as part of a national action plan coordinated by ASN. The data collected (2002) are presented in table 5.

The four most common conventional radiology examinations are radiography of the lower and upper limbs (32%), the spine (16%), the thorax (12%) and the breast (11%); oral radiography accounts for 85% of dental examinations, while scanner examination of the head and spine represent 38% and 26% respectively of the total number of examinations by scanner. Based on the estimated dose values per examination (national or, failing which, European data), the estimated average annual effective dose per person is between 0.66 mSv and 0.83 mSv.

Diagram 6 presents the respective shares of the number of procedures and associated doses, for conventional radiology, scanners, nuclear medicine and interventional radiology.

Diagram 6: breakdown of number of procedures and dose contribution



4 OUTLOOK

Exposure monitoring requires a particular effort in order to better identify the population categories or groups which are most exposed. The interest of this is three-fold: this knowledge should lead to better targeting of risk reduction efforts (optimisation), provide reliable indicators for evaluating the effectiveness of public policy and develop epidemiological surveys for an improved approach to the risk. Thus:

– the results of the measurement of the doses received by workers in 2007, published by IRSN, confirm the drop in the number of monitored workers for whom the annual dose exceeded 20 mSv, as well as the drop in the collective dose, both of which began in 1996. However, these results do not take account of internal dosimetry and dosimetry of the extremities, which are not at present recorded by IRSN. As it is tasked with organising a permanent radiation protection watch, ASN remains particularly attentive to the correct working of the exposure monitoring system set up by IRSN (SISERI), in that the statistics provided constitute valuable national indicators of trends in worker exposure and are useful in assessing the effectiveness of the measures taken by the licensees to apply the optimisation principle;

– exposure of the French population to radon is at present inadequately documented, as the estimates produced by IRSN in 1997 have never been updated and fail to take account of the measurements taken since 1999 in premises open to the public. ASN considers that the future national database containing all available data, under the supervision of the General Directorate for Health, is a vital step towards gaining a clearer understanding of the risk;

– finally, ASN underlines the interest of the forthcoming work to be done by the national patient exposure observatory, run by InVS and IRSN, which should soon benefit from the new social security classification of medical procedures and thus allow monitoring of a cohort of 600,000 patients treated by the private sector for the past 20 years.

The radiotherapy accidents and incidents brought to the notice of ASN in 2006 and 2007 serve to underline the need for a clearer understanding of the possible side-effects of treatment, whether as a result of an incident or associated with the therapeutic strategy decided on by the practitioner. Introduction of the system for notifying serious undesirable events by InVS, interfaced with the radiation protection events notification system implemented by ASN, will constitute very real progress once these effects can be analysed from the medical and scientific viewpoints.

In addition to its regulatory duties, ASN closely monitors developments in research and knowledge in the field of health and ionising radiations, as well as in international radiation protection doctrine. More precisely, in 2009, ASN:

– will conduct a review of current research programmes, the results of which could have an impact on the radiation protection system and its regulation;

– will examine the conclusions of the expert reviews it requested on the occurrence of child leukaemia around basic nuclear installations and on the environmental impact of tritium discharges.