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Volume 7

Radioactive Risk for Humans

Jean-Claude Amiard
Jean-Claude Zerbib

iSTE

WILEY

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coordinated by
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Preface

P.1. Our beliefs

When writing this book, we were guided by a certain number of convictions: independence, freedom of spirit, competence, transparency, scientific rigor, absence of conflict of interest and the right to err in all sincerity.

P.1.1. *Independence*

Our book aims to be scientific and therefore neither pro- nor anti-nuclear, detailing our current scientific knowledge with its strengths and shortcomings. To be independent and responsible, it soon became clear that we needed a limited number of authors. They assume full responsibility for their texts.

P.1.2. *Freedom of spirit*

There is a big difference between fundamental research organizations such as the CNRS, which until recently was one of our employers, and institutional organizations such as the CEA or IRSN, where the hierarchy is very strong. In the former case, researchers are totally free to publish under their own responsibility, whereas in the latter, the hierarchy controls the writings of its employees, resulting in the risk of censorship or self-censorship.

P.1.3. *Competence*

Both authors can legitimately claim competence in this field. One of them has completed two theses (specialist doctorate and state doctorate) involving research in marine radioecology. He has produced some 50 scientific publications in this field, most of them in international peer-reviewed journals. He did not abandon the field altogether, however, as he worked as an expert for CNRS Life Sciences division of the GRNC (*Groupe Radioécologie Nord Cotentin*) from 1997 to 2010. The GRNC has published numerous reports. Since then, he has joined the Scientific Committee, then the Expert Group of ANCCLI (*Association Nationale des Comités et Commissions Locales d'Information*). The Scientific Committee's missions include advising and assisting Local Information Commissions, Local Committees and the ANCCLI in their expert appraisals, acting as an advisory body for Local Information Commissions and ANCCLI actions and publications, and acting as a point of contact for expert committees set up by various French and foreign bodies.

The other author was an engineer at the *Commissariat à l'énergie atomique* (CEA) at the Saclay center. He has devoted his career to protection against ionizing radiation (radioactive measurements, radiation protection of X-ray generators and particle gas accelerators, remediation of contaminated sites). He took part in teaching radiation protection at INSTN (1980–1998) and in the IAEA's international radiation protection courses (1994–1996). In 1996, he was appointed "Senior Expert" at the CEA on the advice of an external scientific commission.

He has taken part in a number of national commissions, including the Castaing commission on the reprocessing of irradiated fuels (1981–1984), the Jean Bernard commission on cancers at the Pasteur Institute (1986–1990), the Radioecology group of the North Cotentin region (GRNC) on the dosimetric impact of radioactive releases from plants (1997–2008), the pluralistic expert group (GEP) on uranium mines in the Limousin region (2006–2013), and the Ministry of Labor commissions on occupational diseases and chemical, physical and biological hazards (1983–1998). He is the author of around 100 articles and co-author of several books on nuclear and occupational health issues.

P.1.4. *Transparency*

Among the multitude of books, scientific publications and gray literature, a choice had to be made. This choice was dictated by scientific quality. Our choices were based on a hierarchy, with French-language publications being the most accessible to the majority. Secondly, work published in peer-reviewed scientific journals, i.e. where peers, other scientists, evaluate and criticize the work before deciding whether its quality justifies publication. As all experts are fallible, this does not certify an absolute value of veracity and quality, but it does contribute significantly to it. Next, all information from official national and international bodies directed our choice. Finally, when we feel that it reinforces information, we include so-called "gray literature", i.e. documents that are much less easily accessible to the public, especially if this literature is old and in the form of printed reports. In this way, anyone can return to most of the sources used in this book.

P.1.5. *Scientific rigor*

Scientific rigor obviously depends on the choice of information and the way in which it is presented. We read a large part of the literature published on this subject, both pro- and anti-nuclear, as well as literature considered to be scientific. We then formed our own opinion. This is what appears in this book.

P.1.6. *Conflicts of interest*

The authors have no conflict of interest in the nuclear field, as they have not carried out any research in this area for many years, and have no shareholdings in companies operating in this niche.

P.1.7. *The right to err in all sincerity*

On such a vast subject, two authors cannot master everything, and they must necessarily trust their peers and the information published. They have not necessarily assimilated all the information correctly, and may therefore have made biased interpretations. All these deviations, if they exist, have been made in all sincerity and the authors apologize in advance to the reader. We undertake to correct them should a second version of this book be published.

P.2. Public opinion

Public opinion on the nuclear phenomenon has evolved over time. Initially, the public's enthusiasm for radium was very strong, and the most far-fetched applications, even dangerous for consumers, were developed, such as the addition of radium-226 to toothpaste, beauty creams and chocolate, alongside more "useful" applications such as luminescent paints. The next applications were military, with the military bombing of Hiroshima and Nagasaki. This is associated with the use of "defense secrecy" for the majority of nuclear applications. The result is strong public distrust and even opposition. The various accidents that have occurred, particularly the most serious ones such as Three Mile Island in 1979, Chernobyl in 1986 and Fukushima in 2011, have accentuated the opposition that now arises whenever a new basic nuclear infrastructure (BNI) is created or modified.

P.2.1. *Public perception of radioactive risk*

The public generally fails to distinguish between danger and risk. Furthermore, risk is measured in terms of probability. As a result, the hazard–risk pair is perceived very differently from one individual to another. Some hazards with uncertain risk potential will be perceived as paramount by the public. Conversely, hazards associated with proven risks will be considered derisory by the public. In the first group we find GMOs, and in the second group alcohol, road accidents, tobacco, etc.

In 2021, the rising concern of the French population was the management of nuclear waste in France: 41% of French people believe that nuclear power plants are a source of high risk, and 48% have the same perception of nuclear waste. This is in line with the 31% of French people who believe that the leading cause of accidental risk is that of a major nuclear accident, such as those at Chernobyl and Fukushima, and that this is the main obstacle to the use of nuclear energy. The second most important potential risk is the storage of radioactive waste (21% of opinions) [IRS 21].

P.2.2. *People trust science, not researchers*

Do you trust scientists to tell the truth about the results and consequences of their work on nuclear energy? The image of scientific experts remains positive for 50% of French people surveyed. The main qualities sought are competence, honesty and independence. Five organizations – the CNRS, ASN, IRSN, HCTISN and CEA – working in the nuclear field had a public confidence rating of over 70% in November 2020 [IRS 21].

P.2.3. *The creation of independent official bodies*

In the past, the protection of humanity and the environment, as well as nuclear safety, were ensured by various services that were too closely linked to industrial interests, such as the CEA. Others, such as OPRI, had had a critical attitude during the Chernobyl accident, and were therefore completely disqualified in the eyes of the public. To compensate for these serious drawbacks, the French government created a number of new bodies that were dependent on the state but independent of the nuclear lobby. These included the IRSN and ASN. The qualities expected of these organizations are competence, independence, rigor and transparency. The gamble has largely paid off.

Alongside institutional experts, there are independent experts who often work for various associations (ANCCLI, ACRO, Global Chance, etc.). Unfortunately, their perfectly independent work is largely neglected, even denigrated or scorned. This is probably due to the fact that independent experts are very often volunteers, and that unpaid work is undervalued.

P.3. The expert and the biases of scientific expertise

P.3.1. *Choice of experts*

The selection of experts for scientific appraisals varies from one field to another. In some cases, experts are co-opted, as in the case of the ICRP, while in others, as in the case of UNSCEAR, the choice is made by political leaders. In all cases, however, scientific criteria are not the only ones involved, but political, industrial and other criteria may also be taken into account.

P.3.2. *The expert's competence*

The scientific subject under discussion in an expert group is generally very broad, and no individual expert can possibly have a complete scientific knowledge of the field. Expertise is therefore necessarily collective, and each expert must at one time or another have confidence in their colleagues.

P.3.3. *The expert's integrity*

Scientific experts are first and foremost people with their own limitations and weaknesses. Before being an expert, a scientific researcher's primary mission (in principle) is to carry out fundamental or applied research. To this end, they are paid employees of a public or private organization. In addition, either to finance their research or to enrich themselves personally, they may accept funding from various public or private organizations. It is therefore not uncommon for conflicts of interest to arise between these institutional or occasional funders and the expert's mission. In the latter case, their "good faith" and independence are far from total.

P.3.4. *Selecting scientific information*

For a long time, the only sources of scientific literature in the nuclear field were the organizations directly involved, which were therefore "biased". It was only after the Chernobyl accident in 1986 that university scientists began to invest in this field of research. The subjects addressed were much more diversified and the concepts renewed. In order to eliminate these independent sources of information, it became common practice in many fields of physical and chemical risk assessment to retain only publications based on "Good Laboratory Practice" (GLP). These standards had been imposed on laboratories dependent on industry to limit scientific drift. However, while academics respect GLP in spirit, they do not apply it sensu stricto. As a result, not all their publications are taken into account. This is particularly true of the summaries produced by the European Food Security Authority (EFSA) [AMI 17].

P.3.5. *Censorship of scientific publications*

P.3.5.1. *Control of nuclear organizations*

Most organizations working in the nuclear field have a pyramid-shaped management structure, and all publications are subject to authorization by the management. As a result, any "disturbing" information can be blocked. Few organizations allow their staff to publish without constraint.

P.3.5.2. *"Defense secrets" and "industrial secrets"*

In the nuclear field, many organizations are military or industrial. They can therefore censor information that could embarrass them on the grounds of "defense secrecy" or "industrial secrecy".

In France, the enactment of the "Transparency, Nuclear Safety" (*transparence et sécurité en matière nucléaire* – TSN) law has considerably changed attitudes (at least for the majority) and made it easier to obtain information about nuclear energy and, in particular, safety. However, there are still a number of gray areas, particularly where national defense is concerned, which are covered by "defense secrecy". We can hope for a positive change in the future, as much of the information retained has no military value, and some of it is an open secret published in specialized journals, but of course cannot be verified.

P.3.6. *Scientific truth*

Scientific truth is by definition provisional, since new scientific advances can call into question our current certainties. In this book, the authors have taken into account the most recent findings.

In many areas, especially those where economic interests are at stake, we can observe divergent interpretations. This is particularly true of human health issues.

For example, the toxicity of tobacco has long been denied by scientists, often linked to the tobacco industry. This is still the case in some countries for asbestos. How can this attitude be explained? Knowledge – and this is no different for toxicology – is gradually gaining ground. So, at the outset, there is a period of time that can unfortunately extend for years, when an isolated piece of information reveals a certain phenomenon, such as the toxicity of tobacco. But does this single result represent an exception or a general phenomenon? New results are often divided between confirming and refuting the first result. This is because, in order to occur, the phenomenon must meet certain conditions (e.g. inter-individual variations in susceptibility to carcinogens, dietary habits).

In science, contrary to popular belief, results are rarely perfectly clear-cut (black and white, yes and no), but are associated with uncertainties. These uncertainties are expressed by a range within which the true answer may lie, associated with a certain probability of being true (95%, 99%). This means that the answer is not absolute; there are 5% or 1% of cases where the answer may be different. Our certainties are therefore only probabilities.

As with any human activity, research involves a number of researchers who lack rigor, and are capable of biasing the interpretation of their observations, or even inventing their results, often in line with the interests of the funders of their work. Limited though it may be, this type of behavior is enough to cause a significant proportion of the population to lose confidence in the profession as a whole. As is the case with the political class, the result for the public is “that we are being lied to”, “that serious things are being hidden from us”. Internet culture allows all kinds of rumors to be spread quickly and widely.

Biological responses are generally highly variable and often follow a normal (or Gaussian) distribution. The same applies to the responses of organisms to radionuclides, whether in terms of bioaccumulation, elimination or damage caused by ionizing radiation. This is true for all living beings, including humans. As a result, it is extremely difficult to identify the main laws and predict the real impact of this type of aggression.

P.3.7. *Our conception of the expert’s role*

A researcher must make available to society, in an accessible form, scientific knowledge concerning the health and environmental benefits, dangers and risks associated with major societal choices, such as the use of nuclear energy.

Our view of the expert's role is that they are not a substitute for decision-makers or society as a whole, but have a duty to enable as many people as possible to make informed choices.

The expert must be able to keep their distance from the generally preconceived opinions of the protagonists, and must assess the case without preconceived ideas and with complete serenity.

P.4. Project objectives

The aim of this book is to estimate the radioactive risk to humans. To do this, the authors will follow the steps of the classic approach presented above. On the one hand, radioactive danger was recognized at the same time as the discovery of radioactivity. On the other hand, the estimation of the radioactive risk to humans is still the subject of lively debate. In this volume, the authors will summarize the scientific work, past and present, that has made it possible to estimate the radioactivity of the anthroposphere and the radioactive contamination of humans. They will list the various routes of exposure to ionizing radiation (external, internal, dietary) and estimate the radiation doses suffered by humans under various conditions (natural for the public and professionals, accidental). Also, the harmful effects of ionizing radiation at various biological levels (molecular, cellular, tissue) and the health effects at the individual level will be reported. The focus will be on occupational diseases caused by radiation. The relationship between doses and adverse effects of ionizing radiation will be discussed for high, medium and low doses. Controversies on this subject will be explained. International and French regulatory values will be provided. Finally, an estimate of the radioactive risk to humans will be proposed.

P.5. Drafting the manuscript

The Preface, Introduction and Chapters 2, 4, 5, 8, 11, 12 and 13 were written by Jean-Claude Amiard, and Chapters 1, 3, 6, 7, 9 and 10 by Jean-Claude Zerbib. Each chapter has been reviewed, corrected, amended, completed and approved by the other co-author.

We wish to thank Professor Philip Rainbow (former Keeper of Zoology, Natural History Museum, London, UK) for reading the English version of the book. We warmly thank him for his time and efforts.

P.6. References

[AMI 17] AMIARD J.C., *Les risques chimiques environnementaux. Méthodes d'évaluation et impacts sur les organismes*, 2nd edition, Lavoisier, Tec&Doc, Paris, 2017.

[IRS 21] IRSN, Baromètre IRSN 2021 sur la perception des risques et de la sécurité par les Français, IRSN, 26/05/2021.

Acronyms and Abbreviations

ABCC: Atomic Bomb Casualty Commission

AChE: Acetyl Choline Esterase

ACRO: *Association pour le Contrôle de la Radioactivité dans l'Ouest* (French Association for the Control of Radioactivity in the West)

AFCN: *Agence Fédérale de Contrôle Nucléaire* (Belgian Federal Nuclear Control Agency)

ALARA: As Low As Reasonably Achievable

ALL: Acute Lymphocytic Leukemia

AMAD: Activity Median Aerodynamic Diameter

AML: Acute Myelogenous Leukemia

ANCCLI: *Association National des Comités et Commissions Locales d'Information* (French National Association of Local Information Committees and Commissions)

ANDRA: *Agence nationale pour la gestion des déchets radioactifs* (French National Radioactive Waste Management Agency)

ARNA: Argentine Nuclear Regulatory Authority

ARPANSA: Australian Radiation Protection and Nuclear Safety Agency

ASN: *Autorité de Sûreté Nucléaire* (French Nuclear Safety Authority)

ASND: *Autorité de Sûreté Nucléaire Défense* (French Defense Nuclear Safety Authority)

BBB: Blood–Brain Barrier

BE: Bystander Effect

BEPN: Binding Energy Per Nucleon

BER: Base Excision Repair

BIOMASS: Biosphere Modelling and Assessment

BIR: Break-Induced Replication

BNI: Basic Nuclear Infrastructure

CCHEN: *Comisión Chilena de Energía Nuclear* (Chilean Nuclear Energy Commission)

CCSN: *Commission Canadienne de Sûreté Nucléaire* (French name of the CNSC)

CDF: Cation Diffusion Facilitator

CEA: *Commissariat à l'Energie Atomique et aux Energies Alternatives* (French Atomic Energy and Alternative Energies Commission)

CLL: Chronic Lymphocytic Leukemia

CNAM: *Caisse Nationale d'Assurance Maladie* (French National Health Insurance Fund)

CNEN: *Comissao Nacional de Energia Nuclear* (Brazilian National Nuclear Energy Commission)

CNSC: Canadian Nuclear Safety Commission

COGEMA: *Compagnie Générale des Matières Nucléaires*

CSN: Spanish Council for Nuclear Safety

CVD: Cerebrovascular Disease

DAM: *Direction des Applications Militaires* (French Directorate of Military Applications)

DCN: *Direction des Constructions Navales* (French Directorate of Shipbuilding)

DDR: DNA Damage Response

DDREF: Dose and Dose-Rate Effectiveness Factor

DFD: *Deutsch-Französischer Direktionausschuss* (German-French Management Committee)

DNA: Deoxyribonucleic Acid

DS86: Dosimetry System from 1986

DSB: Double Strand Break

DTPA: Diethylene Triamine Penta-acetic Acid

DU: Depleted Uranium

EDF: *Électricité de France* (French multinational electric utility company owned by the government of France)

EMRAS: Environmental Modelling for RAdiation Safety

ENSI: Swiss Federal Nuclear Safety Inspectorate

ERR: Excess Relative Risk

EU: European Union

FAO: Food and Agriculture Organization

GRNC: *Groupe Radioécologie Nord-Cotentin* (Radioecology Group of the North Cotentin Region)

GRS: *Gesellschaft für Anlagen- und Reaktorsicherheit* (Society for Device and Reactor Safety)

HAEA: Hungarian Atomic Energy Authority

HBNRA: High Background Natural Radiation Areas

HCTISN: *Haut Comité pour la Transparence et l'Information sur la Sécurité Nucléaire* (French High Committee for Transparency and Information on Nuclear Safety)

HLNRA: High-Level Natural Radiation Areas

HOS: Human Osteoblast Cells

HR: Hazard Ratio

HTO: Tritiated Water

IAEA: International Atomic Energy Agency

IAEC: Israel Atomic Energy Commission

ICRP: International Commission on Radiological Protection

ICRU: International Commission on Radiation Units and Measurements

IHD: Ischemic Heart Disease

ILO: International Labour Organization

INFN: *Istituto Nazionale di Fisica Nucleare*

ING: Incorporation by Ingestion

INH: Incorporation by Inhalation

INJ: Incorporation by Injection

INRS: *Institut National de Recherche et de Sécurité pour la Prévention des Accidents du Travail et des Maladies Professionnelles* (French National Research and Safety Institute for the Prevention of Occupational Accidents and Diseases)

INSERM: *Institut National de la Santé et de la Recherche Médical* (French National Institute for Health and Medical Research)

INSTN: *Institut National des Sciences et Techniques Nucléaires* (French National Institute for Nuclear Science and Technology)

INWORKS: International Nuclear Workers Study

IPSN: *Institut de Protection et de Sûreté Nucléaire* (French Institute for Nuclear Protection and Safety)

IR: Ionizing Radiation

IRA*:* Integrated Risk Assessment

IRSN: *Institut de Radioprotection et de Sûreté Nucléaire* (French Institute for Radiation Protection and Nuclear Safety)

ITER: International Thermonuclear Experimental Reactor

KI: Potassium iodide

KINS: Korea Institute of Nuclear Safety

LDIR: Low-Dose Ionizing Radiation

LDRIR: Low-Dose-Rate Ionizing Radiation

LET: Linear Energy Transfer

LNT: Linear Non-Threshold

LRWT: Linear Relationship Without Threshold

LSS: Life Span Study

MAAD: Median Active Aerodynamic Diameter

MRCP: Mesh-type Reference Computational Phantoms

NAS: US National Academy of Sciences

NDK: *Nükleer Düzenleme Kurumu* (Turkish Nuclear Regulatory Authority)

NEA: Nuclear Energy Agency

NNSA: China's National Nuclear Safety Administration

NRA: Bulgarian Nuclear Regulatory Agency

NRA: Japanese Nuclear Regulation Authority

Nramp: Natural resistance-associated macrophage proteins

NRC: National Research Council

NCRP: National Council on Radiation Protection and Measurements

NTE: Non-Targeted Effects

OAP: Thai Office of Atoms for Peace

OBT: Organically Bound Tritium

OD: Occupational Diseases

OECD: Organization for Economic Cooperation and Development

ONR: UK Office for Nuclear Regulation

OPT: Oligo Peptide Transporters

OR: Odds Ratio

PAH: Polycyclic Aromatic Hydrocarbons

PAR: Population Attributable Risk

PCB: Polychlorobiphenyl

RBE: Relative Biological Effectiveness

RERF: Radiation Effect Research Foundation

RIBE: Radiation-Induced Bystander Effect

RIFE: Radioactivity in Food and the Environment

RIGI: Radiation-Induced Genomic Instability

RNA: Ribonucleic Acid

ROS: Reactive Oxygen Species

RPL: Radio-Photo-Luminescent

RR: Risk Ratio