IPSN

ELEMENTS OF NUCLEAR SAFETY

Jacques Libmann

les éditions de physique

INSTITUT DE PROTECTION ET DE SURETE NUCLEAIRE

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Foreword

This basically educational document draws much of its substance from all the various activities of the Institute for Nuclear Safety and Protection (IPSN), the technical support body of the Nuclear Installation Safety Directorate (DSIN). The latter organizations however may under no circumstances be considered liable for its contents.

Its purpose was to heighten awareness among analysts and more generally among all those concerned by nuclear safety. The safety picture presented is consequently not intended to be well-balanced. It is moreover imbued with the activities and viewpoints of the IPSN, which is only one of the safety organisms concerned.

The present document is an extensively supplemented revision of work published in 1988 by the National Institute for Nuclear Science and Technology (INSTN) under the title "Approche et analyse de la sûreté des réacteurs à eau sous pression". As in the previous case, this work would not have been possible without the technical and financial assistance of the DSIN. The personal acknowledgments featured in the 1988 publication remain intact for the present version, as follows: Monique Libmann; Marie-Claire Dupuis, Bernard Barrachin, André Cayol, Bernard Fourest; Daniel Quéniart, Yves Chelet, François Cogné.

The basic raw material for a general review of the activity of a large group is the actual work of the members of the group considered. This was, of course, the case for the present document and I should like to mention in a far from exhaustive list some of those on whom I relied for assistance:
Roland Avet-Flancart, Bernard Barbé, Alain Bardot, Bernard Barrachin, Bernard Bartholmé, Geneviève Beaumont, Claude Birac, Christine Bonnet, Jean Bourgeois, Louis Brégeon, Jacques Brisbois, Jean-Paul Bussac, Gérard Cadolle, Marc Champ, Yves Chelet, Alain Chesnel, Jean-Pierre Clausner, François Cogné, Yvon Cornille, Patrick Cousinou, Bernard Crabol, Michel Delage, Gérard Delettre, Gérard Depond, Yves Droulers, François Ducamp, Jacques Duco, Marie-Claire Dupuis, Véronique Fauchille, Jean Fauré, Christine Feltin, Bernard Fourest, Denis Goetsch, Christian Giroux, Alain

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Consistency of principles and their expression was once again assured by Daniel Quéniart, who thus made a decisive contribution to the contents of this text.

The readability of the book, both for French and foreign readers, was vastly improved thanks to the advice and comments of Nathalie Rutschkowsky.

Philippe Vesseron and Henri Métivier fostered its publication in this form, whilst Etienne Benoist encouraged its translation into English and Russian.

To Monique Libmann and Monique Roy was entrusted the thankless task of rereading.

I am most honored that Mr. André-Claude Lacoste, Director of the DSIN and Chairman of the Board of Management of the IPSN, has accepted to preface the book.

I thank them all. Needless to say, any errors and imperfections which may nevertheless have been overlooked remain my entire responsibility.

Jacques Libmann

Preface

Like many other industrial safety fields, nuclear safety has developed considerably over the last few decades. An essential component of the very notion of safety is doubtless the ceaseless quest for improvement.

The impact of these developments on organizations is in part related to the more widespread use of nuclear energy. The prime responsibility of nuclear operators for the safety of their plants is now clearly acknowledged by the International Convention on Nuclear Safety, as is the necessity for each country concerned to constitute a competent safety authority, independent of organisms promoting nuclear energy. It was only in 1973 that such a nuclear safety authority (SCSIN) was set up in France, as a department of the ministry of industry. Twenty years later, it became the DSIN (nuclear installation safety directorate), responsible to the ministers for industry and for the environment respectively. For several years now, the running of this department has been supervised by the Parliamentary Office for Assessment of Scientific and Technological Options and the implementation of nuclear safety statutory provisions is currently being considered.

Technical repercussions have also been extensive, since ideas have considerably progressed in France since the initial adoption of the American PWR design, accompanied by its already voluminous package of regulatory or pararegulatory texts. The EDF and Framatome engineers, together with those of the safety authority and its technical support structure, the IPSN, had first to become thoroughly acquainted with the basic reactor type before gradually moving on to a more practical approach, involving the control of accidents considered as beyond design basis events in American practice and even those culminating in core meltdown. Deep thinking along these lines even led to certain previously adopted but inadequately validated criteria being called into question, such as the use of fuels with high burnup fractions.

These gradual developments, prompted by know-how advances, whether based on operating feedback or research and development results, are the subject matter of Jacques Libmann's book.

Throughout his career at the IPSN, Jacques Libmann has personally followed all the varied details of this progression, as now witnessed by his book. Many of you will remember him from their training courses, both in France and abroad, when he succeeded in convincing his listeners of the soundness of the basic safety principles which have gradually been defined. The publication of this book will doubtless widen his audience even further and will be beneficial to all those seeking either an introduction to nuclear safety or further insight into specific aspects of the subject.

The time history approach has the advantage of showing how real improvements are achieved, sometimes after false starts, by pragmatic research where accepted ideas may have to be called into question. Current developments are aimed beyond national contexts at European, or even worldwide harmonization of safety practices, together with significant improvements on the safety level presently attained. This is notably the goal of the future PWR developed by the French and German utilities and plant builders (EPR project).

May Jacques Libmann's book assist all those, whether they be designers, operators or safety authority specialists, who, in France or abroad, are responsible for nuclear plant safety issues!

André-Claude LACOSTE

Directeur de la Sûreté
des installations Nucléaires

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Introduction

Nuclear installations present a specific risk in that they all contain, by definition, more or less substantial quantities of radioactive products. These can result in the exposure of individuals, populations or the environment to ionizing radiation and the consequences thereof. Nuclear installations for electricity generation fall, of course, in this category.

Other sources of energy also involve risks, but our present purpose is not to draw comparisons. Moreover, we are well aware of public sensitivity in this respect, where radioactivity effects are associated far more with the military explosions of Hiroshima and Nagasaki, and now with Chernobyl, than with natural radioactivity or the benefits of radiotherapy. Our intention here is simply to present the methods and concepts used in the nuclear industry to ensure a satisfactory safety level for this activity.

Safety results from a set of technical and organizational measures taken at all stages in the life of an installation to ensure that its operation and, more generally speaking, its very existence, present a sufficiently low-level risk as to be deemed acceptable for the staff, the general public and the environment.

So what is actually involved is:
- ensuring normal operating conditions which are conducive neither to excessive exposure of workers nor to release to the environment of radioactive waste with a high activity level
- incident and accident prevention
- limiting the consequences to workers, populations and the environment of any incidents and accidents which could nevertheless occur.

This gives rise to provisions covering plant operation, but also its design, construction and decommissioning.

It is to be noted that the idea of an acceptable risk is not grounded on clearly defined, absolute criteria, but is rather the result of choices of a sociopolitical nature which may evolve over a period of time and may differ from one country to another, depending on local economic conditions. In this context, it is the role of the technicians to propose, but the final decision is based on political assessments integrating other contingencies.

For any given installation, the process begins with identification of the nature and extent of the risks entailed. Only after this has been done can methods for ensuring safety be defined and analyzed.

Several decades have now elapsed since nuclear plant construction and operation began in France. The reactors of the first type used in France, which were natural uranium-fuelled, graphite-moderated and CO_2-cooled, have now all been shut down. Several of the installations currently in service were built to earlier standards, at least as regards technological developments and safety issues.

Most of the pressurized water reactors presently operating in France were designed on the basis of the American plants under construction at the end of the sixties and the beginning of the seventies, at a time when world experience in this type of undertaking was limited.

It is consequently not surprising that, although the basic principles defined at the outset of a project are not easily called into question, safety criteria approaches and analysis methods have considerably altered over the period of time involved.

Now that substantial experience has been acquired, we are, or course, able to check whether the principles underlying the initial approach are still satisfactory and to compare actual plant behavior with the estimates made beforehand. The world's two most dramatic nuclear accidents, Three Mile Island in 1979 and Chernobyl in 1986, figure largely in this analytical process, without however overshadowing the many minor difficulties to be contended with in the daily running of an installation.

Rather than describe current approaches to safety from a static status angle, we have opted for a partly historical presentation which reveals more clearly their dynamic and evolutive character. We shall base most of this presentation on the pressurized water reactors operated in France, although many other examples will also be used.

In this document, we shall consider successively:

- the deterministic approach, which is the main safety approach method
- safety analysis methods based on accident analysis
- the enhancement of these methods by development of the probabilistic safety approach and preparation for the management of particularly severe accident situations
- operating feedback
- subsequent evolution paths and the international dimension.

Each subject will be illustrated with a number of examples.

General topics such as the human factor or the importance of quality, could have been dealt with in separate chapters, but we have preferred, on the contrary, to avoid isolating them so that they can be referred to in the many contexts directly concerned by them.

Finally, we shall insofar as possible base our discussion of the elements of this approach on general aspects, applicable to all nuclear installations, for it will be seen that if responses in each case must be adapted to specific potential risks, the same types of questions re-occur and have to be systematically examined.

In order to situate the purpose of nuclear safety, we shall summarize in an introductory chapter the biological effects of radiation together with the main basic principles of radiation protection. This should enable the reader to better comprehend the extent of the consequences of the phenomena discussed.

Similarly, safety awareness and practice involve a sharing of responsibilities defined by regulatory texts. In order to conserve the technical and philosophical rather than administrative disposition we have adopted, the second chapter will describe the organizational principles governing relations between the safety partners. This will give rise to reflections on the determination of "acceptable" risks and on what is now referred to as Safety Culture, to which we trust the present document will contribute.

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1 Radioactivity and the biological effects of ionizing radiation

At the International Conference on the Safety of Nuclear Energy: Strategy for the Future, held in Vienna (Austria) on September 2-6, 1991, it was deemed advisable to present the basic biological effects of radioactivity to enable at least overall understanding, with a view to prevention, of possible radiological consequences of abnormal situations and of the basic principles of radiation protection. It is on the same grounds that the present work begins with a chapter on this subject. The text is adapted from the conference document prepared by an international working party entrusted with presenting the basic principles of safe use of nuclear energy. It draws extensively on the conclusions formulated by the organizations competent on this question, the International Commission on Radiological Protection (ICRP) and notably its publication No. 60, but also on certain more recent observations on the populations exposed following the Chernobyl disaster.

1.1. Units used

The radioactivity unit is the becquerel (Bq), equal to 1 disintegration per second. As this unit is extremely small, multiplying prefixes are often employed: mega (M) = 10^6, giga (G) = 10^9 or tera (T) = 10^{12}.

The former unit is the curie (Ci), equal to 3.7 10^{10} disintegrations per second or becquerels and historically defined as the activity of one gram of radium 226. Since this unit is relatively large, minimizing prefixes were used: micro (μ) = 10^{-6}, nano (n) = 10^{-9}, pico (p) = 10^{-12}.

$$1 \text{ Ci} = 37\ 10^9 \text{ Bq or } 37 \text{ GBq};$$

$$1 \text{ Bq} = 27\ 10^{-12} \text{ Ci or } 27 \text{ pCi}.$$

Two units are used to express radiation effects on the human body. The gray (Gy) expresses the energy deposited in matter by a particle or radiation. 1 gray = 1 joule per kilo of material. It is the SI absorbed dose unit, replacing the former rad (1 Gy = 100 rad).

The shorter the path of each energy depositing particle, the greater will be the potential noxiousness of the absorbed dose.

For comparison purposes, quality factors are used to express absorbed doses of any type in terms of dose equivalents for reference X and γ radiation effects. This quality factor is, by definition, 1 for electrons and X and γ radiation, 20 for alpha particles and heavy nuclei and from 5 to 20 for neutrons and protons. The dose equivalent is expressed in sievert (Sv). The former unit is the rem (1 Sv = 100 rem).

Each tissue and organ has a specific sensitivity to cancer risks. For 100 cancers observed following homogeneous external exposure, there are 12 lung cancers, 5 breast cancers and 1 skin cancer, for instance. So a weighting (or sensitivity) factor is introduced to transpose the dose equivalent into an effective dose.

In the event of internal contamination, irradiation continues until the radioelement responsible has been removed. In this case, we calculate the dose commitment due to the contamination, extrapolated over the next 50 years. In accordance with current regulations, this calculation is performed at the time of contamination. Effective and committed doses are also expressed in sievert.

In accordance with regulatory practice, the term "dose" shall generally refer in what follows to an effective dose.

The relationship between a becquerel and the corresponding gray or sievert number depends on the particle or radiation energy and its mode of interaction with the substance considered and, in the case of internal contamination, on the length of time the radioelement stays inside the organism.

1.2. Natural radioactivity

Since the origin of man, humanity has been exposed to a wide spectrum of natural ionizing radiation. This exposure is due to cosmic radiation, gamma radiation from the earth and radioactive products naturally present in the human body, originating from food and water (mainly lead 210 and potassium 40) and from inhalation (mainly radon 222).

The annual dose due to these natural sources averaged over all populations of the globe is between 2 and 3 millisievert (mSv), but varies between 1 and 5 mSv according to the place considered. Under average conditions, the contributions of the cosmic rays, the gamma rays from the ground and ingested products are approximately the same and equal to 0.3 to 0.4 mSv. So the fraction due to radon inhalation is much larger, representing up to 40% of this natural irradiation. It varies considerably according to place, dwellings, living conditions.

- Other experience (operating experience of basic nuclear facilities, "standard practice") has enabled the processes or codes used to be validated; in such event, it shall be systematically determined that the assumptions are correct and fall within the scope of such processes or codes.
- Insofar as it is possible to make properly any necessary changes, the facility commissioning tests may be sufficient to confirm the achieved results; the number of cases in this category shall remain sufficiently limited so that possible changes necessary at an advanced stage of construction remain limited.
- The studies for which there are no technical control means independent of those used and a list of which is included as such with all necessary support in the safety report.

In these three cases, the procedures for the follow up of the studies provide evidence, with all necessary support, of the extent of the areas in which the special control measures are not implemented.

Finally, studies aiming only at improving assessment of the available tolerances with respect to situations not allowed for in the design are subject to adapted procedures; in such event, the use of simplified confirmation calculations is no longer required but they shall be used insofar as possible.

Article 15

For certain activities initiated before filing of the basic nuclear facility construction permit application, and in particular for preliminary plan activities, the Order's provisions may be adapted or not applied entirely insofar as no action difficult to reverse under the decisions made for the safety of the future facility can result therefrom.

Article 16

(mentioned as a reminder).

Article 17

This article takes into account the diversity of basic nuclear facilities (power reactors, research reactors, fuel enrichment, manufacturing and reprocessing plants, waste storage centers, accelerators, irradiators, laboratories, etc.), the diversity of the phases in which they now stand and the time necessary for the establishment, if need be, of new measures.

The Order is obviously not applicable to activities completed on the date of publication of the Order in the Official Journal. It applies however as provided in this article to future and continuing activities.

Article 18

Requests for waiver of the Order will be handled by the Head of the SCSIN who will consult, insofar as need be, the competent experts or groups of experts, in particular the standing groups responsible for studying the technical aspects of the safety of nuclear facilities.

Article 19

Like the other provisions of the regulation covering basic nuclear facilities, the order applies in the strict sense only to the basic nuclear facilities operated or to be operated in France.

However, a supplier may happen to perform, or make others perform, in France, a significant part of the activities devoted to design or construction of a nuclear facility located or to be located abroad. If the involved supplier so requests, measures will be taken to enable provisions of the order enforceable in France to be applied under the same conditions as if the nuclear facility were to be installed in France, considering the supplier as an owner, as defined in the Order, during the design and construction period. The Head of the SCSIN shall then be instructed to enforce the Order.