CENTRE D'ETUDE SUR L'EVALUATION
DE LA PROTECTION DANS LE DOMAINE NUCLEAIRE

cepn

REPORT N° 276

PROPOSED CLASSIFICATION SCALE FOR RADIOLOGICAL INCIDENTS AND ACCIDENTS

Pascal CROÜAIL, Christian LEFAURE

November 2002

Contract DGSNR 02/2/43/0002

SIEGE SOCIAL ET ADMINISTRATIF :

ROUTE DU PANORAMA BP 48 F-92263 FONTENAY AUX ROSES CEDEX
TEL : +33 1 58 35 74 67 FAX : +33 1 40 84 90 34
E-MAIL : sec@cepn.asso.fr WEB : http://www.cepn.asso.fr/

ASSOCIATION DECLAREE CONFORMEMENT A LA LOI DU 1 JUILLET 1901 SIRET : 310 071 477 00031 N° DE TVA : FR60310071477

ACKNOWLEDGEMENTS

We wish to thank our colleagues at the Nuclear Protection Evaluation Centre (CEPN) for their help in drafting this report, particularly J. Lochard, C. Schieber and J.P. Degrange for their advice and contributions regarding methodology, and D. Collin for his help in drafting the appendices.

We also extend our thanks to the members of the Working Group of the General Directorate for Nuclear Safety and Radiological Protection (DGSNR) set up to determine radiological protection incident criteria for the comments made at our joint meetings. We trust we have made allowance for them as accurately as possible.

CONTENTS

LIST OF TABLES AND FIGURES

ABSTRACT

The scale proposed in this report is intended to facilitate communication concerning the severity of incidents and accidents involving the exposure of human beings to ionising radiations. Like the INES[1], it comprises eight levels of severity and uses the same terms (accident, incident, anomaly, serious and major) for keeping the public and the media informed.

In a radiological protection context, the severity of an event is considered as being directly proportional to the risk run by an individual (the probability of developing fatal or non-fatal health effects) following exposure to ionising radiation in an incident or accident situation. However for society, other factors have to be taken into account to determine severity.

The severity scale proposed is therefore based on assessment of the individual radiological risk. A severity level corresponding to exposure of a member of the public in an incident or accident situation is determined on the basis of risk assessment concepts and methods derived from international consensus on dose/effect relationships for both stochastic and deterministic effects.

The severity of all the possible exposure situations — worker exposure, collective exposure, potential exposure — is determined using a system of weighting in relation to situations involving members of the public.

In the case of this scale, to indicate the severity of an event, it is proposed to make use of the most penalising level of severity, comparing:

- the severity associated with the probability of occurrence of deterministic effects and the severity associated with the probability of occurrence of stochastic effects, when the event gives rise to both types of risk,
- the severity for members of the public and the severity for exposed workers, when both categories of individuals are involved,

---

1 The International Nuclear Event Scale (INES), User's Manual, 2001, IAEA, Vienna, 2001.

- the severity on the proposed radiological protection scale and that obtained using the INES, when radiological protection and nuclear safety aspects are associated with the event in question.

1. REASONS FOR HAVING A SEVERITY SCALE FOR RADIOLOGICAL INCIDENT AND ACCIDENT SITUATIONS

Given that the public is highly sensitive to radiological protection issues, radiological incidents and accidents are given wide media coverage, regardless of their actual degree of severity. It is therefore essential that the radiological protection authorities have a simple tool whereby they can communicate with the public and put the various radiological incidents and accidents into perspective on the basis of their relative severity.

As regards the protection of human beings, the severity of an event is considered as being directly proportional to the risk run by an individual (the probability of developing fatal or non fatal health effects) following exposure to ionising radiation in an incident or accident situation.

The aim therefore is to propose a tool that will allow the experts to make allowance for the various aspects of this risk and to quickly attribute to it a degree of severity that will make the quantitative assessment of it more meaningful to the media and the wider public, using known, commonly-used qualitative terms (accident, incident, serious, major etc.)[2].

The aim is not to take a pedagogical approach to the radiological risk or to put it into perspective as regards other risks encountered in daily life (tobacco, AIDS etc.).

To be effective, a tool such as this must not only be understandable and easy to use, it must also be acceptable to all those involved. Whenever possible, there should be no vague, contradictory information.

If it is to be credible, the tool must be based on international consensus on the knowledge and assumptions associated with the health effects of ionising radiation and on the dose-effect relationships used to manage radiological risks.

---

2 These terms are used in the context of the INES

To be reactive, the tool must be based on a system that allows events to be classified in a simple manner using available assessment techniques (software, charts) which resume the state-of-the-art in dose-effect relationships.

To be understandable, it should not involve terms that are too technical: the general public has great difficulty understanding information that makes use of the official system of dose units, which is complicated and unfamiliar, and in grasping the difference between stochastic and deterministic effects or situating the severity of events on the basis of the relationships between the various types of radiation, the exposure levels and the effects.

Furthermore, the tool must also be capable of covering a very wide range of "possible" events corresponding to different types of exposure (internal, external etc.) resulting in a wide range of doses (more than ten orders of magnitude!) that could be received by different types of individuals (workers, the public, patients) in very different sectors of activity (non-nuclear industry, medical, nuclear industry).

A communication tool, known as the INES[3], is already being used by a number of regulatory authorities for incidents and accidents with radiological aspects, but its appropriateness in the field of radiological protection is open to discussion. In the light of a bibliographical study of severity scales[4], it has become apparent that there should be only one communication scale for each type of event (with the appropriate number of severity levels and its own terms) and several classification criteria: nuclear safety, radiological protection of individuals etc.). Each event is classified by the experts according to the appropriate criteria and the degree of severity that is communicated corresponds to the most severe criterion.

---

3 The INES was devised essentially to provide information on the severity of events from a nuclear safety point of view; it includes individual exposure factors but the mode of classification it employs is not suitable for radiological protection issues (see Section 3 below).

4 This study, entitled « Les échelles de gravité: synthèse bibliographique » (D. Rittore, P. Croüail, C. Lefaure. CEPN note 99/17 dated December 1999) showed that when an event could be classified according to several criteria, it was often allocated the severity of the most severe criterion. Thus on the atmospheric pollution scale ATMO, pollution is quantified for several pollutants: sulphur dioxide, nitrogen dioxide, ozone, particles etc. The pollutant that is deemed to be the worst determines the level of severity of the event that is broadcast to the public. The same rule applies to the industrial accident severity scale developed by the French ministry for the environment in the context of the SEVESO Directive.

If information is to be given on events that involve several types of risk (radiological and non-radiological), it must be possible to apply the approach adopted in a general manner, not specifically to radiological risks. Thus, in the case of an event involving exposure to toxic chemicals and ionising radiation, the probability of developing health effects can be linked to either one of the two types of exposure. When exposure-risk relationships are available for toxic chemicals, a classification can be made according to other criteria and the public can be informed of all the risks on the basis, once again, of the most severe criterion.

This report deals only with assessment of radiological protection of individuals: protection of the environment against radioactive, toxic substances or other pollutants for example are not covered.

Lastly, the tool has three further objectives:

- To make allowance for the number of individuals exposed during the incident or accident.
- To highlight events that reflect shortcomings in the radiological protection system and those that are due to non-compliance with the regulatory rules in force.
- To estimate the severity of a potential risk, i.e. a risk corresponding to the exposure to which individuals could have been subjected if they had been present or present for longer at the scene of the event.

2. EVENTS COVERED BY THE SCALE

The scale proposed can only be used to characterise radiological incidents and accidents, hereinafter referred to as events. A clear definition therefore has to be given of what is meant by events occurring in incident and accident situations. A number of exposure situations can be eliminated from the scope of the scale from the outset.

2.1. Exposure situations not covered by the proposed scale

Most situations involving exposure to naturally-occurring radiations are, by nature, of the non-incident type (exposure to cosmic radiation, internally deposited natural radionuclides etc.) and do not fall into the category of exposure events covered by the scale. It would also appear that other types of exposure to naturally-occurring radiation should be excluded in the light of current practices and regulations: examples are exposure to radon in dwellings or exposure to enhanced levels of naturally-occurring radionuclides, but future changes in the regulations could mean that some situations could be classified as incidents.

“Normal” occupational exposure, “normal” medical exposure (i.e. that which is justified, planned and optimised) and controlled exposure (in the case of so called “interventions” for example) are not covered by the scale.

Past events (fallout from nuclear weapons testing, the Chernobyl accident etc.) should be classified with the proposed severity scale. However, the corresponding long-term residual exposures are not supposed to be assessed using the proposed scale (as it does not constitute a "new" event).

2.2. Exposure situations covered by the proposed scale

Contrary to the examples given above, all events leading to exposure in incident and accident situations that is combined with normal or controlled exposure or exposure to background radiation and which occurs in industry (nuclear energy and others) or in the medical field, could be assessed using the scale proposed. Radiological incidents and accidents leading to patient exposures are situations that will be covered by the proposed scale but, a preliminary work must be done with professionals of the medical field to determine exactly which events can be considered as incidents or accidents.

3. THE POSITION OF THE RADIOLOGICAL INCIDENT AND ACCIDENT SEVERITY SCALE IN RELATION TO THE INES

3.1 Inability of the INES to make allowance for radiological protection incidents

The INES (International Nuclear Event Scale) was devised as a system for publishing information about events involving nuclear safety that could be easily understood by the media and the general public. Originally (March 1990), the INES applied only to events that occurred in or were caused by nuclear facilities and which involved nuclear safety.

When it was revised in 1992, the designers of the scale introduced criteria that allowed events to be classified according to the radiological protection aspect. Even more recently, in February 2001, a new version of the INES user's manual was published by the International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency of the OECD. According to the designers, the scale should now “apply to all events involving radioactive materials (including transport)”, thanks to the 1992 review and, to an even greater extent, the 2001 publication. The table overleaf summarises the quantified radiological protection criteria used to classify events on the INES.

When examined in depth, a number of inconsistencies and interpretation problems are brought to light which make communication with the tool problematic whenever radiological protection is involved. These limitations, which we describe below, explain why we are proposing a logic that differs somewhat from the INES, while remaining as consistent as possible with it (see Section 3.3 below).

Table 1. Radiological protection criteria already included in the INES

	Area of impact		
	Off-site impact	**On-site impact**	**Impact on defence in depth**
7 Major accident	Major release - Widespread health and environmental effects No values for doses to the public		
6 Serious accident	Significant release - likely to require full implementation of planned countermeasures No values for doses to the public		
5 Accident with off-site risk	Limited release - likely to require partial implementation of planned countermeasures No values for doses to the public	Severe damage to reactor core/ radiological barriers	
4 Accident without significant off-site risks	Minor release – public exposure of the order of prescribed limits Maximum dose received by the public (critical group) **a few mSv** or irradiation > **5 Gy** (loss of source or transport)	Significant damage to reactor core/radiological barriers/fatal exposure of a worker Irradiation > **5 Gy** of one or more workers	
3 Serious incident	Very small release – public exposure at afraction of the prescribed limits Maximum dose received by the public (critical group) **a few tenths of 1 mSv** or irradiation of the order of **1 Gy** (loss of source or transport)	Severe spread of contamination/ Acute health effects to a worker General irradiation of one or more workers of the order of **1 Gy** Superficial irradiation to the bodies of one or more workers of the order of **10 Gy**	Near accident no safety layers remaining
2 Incident		Significant spread of contamination: Dose rate > 50 mSv/h (at 1 m) Overexposure of a worker (beyond the regulatory dose limits) **(Effective dose > 20 mSv)**	Incidents with significant failures in safety provisions
1 Anomaly			Anomaly beyond the authorised operating regime
0 Deviation	No safety significance		
Events not on scale			

3.1.1. No clear distinction between off-site and on-site outside the nuclear context and in the radiological protection field in general

The INES makes a distinction between “off-site” events (which are the only ones with the potential to produce accident levels higher than 4) and “on-site” events. This is a difficult distinction to make in many medical and non-nuclear industrial facilities for which there is no exclusion zone for the public. Members of the public likely to be exposed to ionising radiation in incident and accident conditions live and work close to or even in these facilities. The distinction between off-site and on-site is therefore not appropriate in these cases, even though it is perfectly suited to nuclear safety. On the basis of the radiological protection system and the regulations that result from it, it would appear far more helpful to differentiate between the types of individuals who are exposed (members of the public or workers) rather than where an incident occurs.

3.1.2. Shortcomings and inconsistencies in the INES as regards radiological protection for “off-site consequences”

For off-site consequences, the INES gives severity levels higher than 3 (i.e. events are qualified as being “serious incidents” at least). This is quite justified where nuclear safety is involved since there is a loss of containment of the nuclear materials outside the facility. But the desire to put radiological protection criteria on the same scale means that the severity of radiological incidents is over or underestimated and there is an amalgamation of incidents which are quite different as regards radiological protection.

Thus:

- Serious incidents (Level 3) are taken as being incidents that result in a dose to the critical group of more than a few tenths of one millisievert (in the case of incidents where releases occur); accidents (Level 4) are events that result in a dose to the critical group of more than a few millisieverts (in the case of incidents where releases occur). These events correspond to a probability of occurrence of exposure-induced death of the order of 10^{-6} and 10^{-5} respectively, over an entire lifetime,
- Serious incidents (Level 3) are taken as being incidents that result in general irradiation (“whole body”) of more than 1 gray (in the case of exposure to a lost source or a radioactive material transport accident); accidents (Level 4) are events that result in general irradiation of more than 5 grays (in the case of exposure to a lost source or a radioactive material transport accident). These events correspond

respectively to a high probability of occurrence of a non-lethal deterministic effect and to a semi-lethal dose (in other words, 50% of the individuals irradiated to this extent die within thirty days).

From a radiological protection point of view, we can hardly justify the fact that such disparate dose levels, and therefore risk levels (with a difference of almost four orders of magnitude!) are placed at the same severity levels on a scale designed for communication purposes. In this case, the INES provides inconsistent information.

- All events resulting in doses to the public of less than 1 Gy cannot be classified (since no releases are involved) and are amalgamated below Level 3.

But events resulting in doses of less than 1 Gy are those that are the most likely to occur. Therefore the INES cannot be used to characterise or appropriately indicate the severity of the most common types of incident.

3.1.3. Shortcomings and inconsistencies in the INES as regards radiological protection for "on-site consequences"

Events with on-site consequences can be classified as Levels 2, 3, 4 and 5 on the INES. However, using radiological protection criteria, events can only be classified at Levels 2, 3 and 4. These criteria concern worker exposure only, such as:

- doses that are higher than the annual regulatory limit — Level 2 incident (in France, 50 mSv/year was the limit in force in 1992),
- the whole body irradiation "of one or more workers" with doses of more than 1 Gy (non-lethal deterministic effects probable) or 10 Gy in the case of superficial irradiation of the body — Level 3 serious incident , and
- irradiation of one or more workers receiving a semi-lethal dose (more than 5 Gy) — Level 4 accident.

Most of the other criteria are qualitative (damage to radiological barriers, spread of contamination, severe effects on health etc.) and may give rise to different interpretations and classifications for incidents and accidents which nonetheless have similar consequences for health.

It is true that the amalgamations are less obvious than in the case of exposure of the public and it could be possible to place events resulting in doses lower than the annual limit for workers at severity levels of less than 2 on the scale without calling into question the logic of the INES. Conversely, it is illogical from a radiological risk point of view to place all doses between the annual exposure limit and 1 Gy at the same level of severity.

3.1.4. Inconsistencies of the INES as regards radiological protection between "off-site" and "on-site" consequences

The possibility of members of the public being exposed during on-site events is not an option with the INES, nor is it envisaged that workers might be exposed off-site. But many incidents involve both the public and workers.

Lastly, it should be emphasised that the INES puts at the same level, i.e. Level 4 accident, fatal exposure of a worker (or semi-lethal exposure of several workers) and a dose of a few millisieverts received by a member of the critical population group, after a release. By definition, during events such as this, the dose received by the rest of the population is lower again by one order of magnitude, i.e. a few tens of millisieverts. As regards the risk for the health of individuals and considering what is socially acceptable, it is perfectly clear that these two events are on a completely different scale. In radiological protection terms, it is unacceptable to put them at the same level of severity.

3.1.5. Conclusion

Given the various points mentioned above, it is clear that it is very difficult, or even impossible, to use the INES as a tool for communicating with the public and the media on the subject of radiological protection incidents and accidents in anything other than the nuclear energy field, and even there when nuclear safety is not involved.

3.2. Compatibility of the proposed scale with the INES

Despite the problems encountered when using a scale such as the INES, as described in Section 3.1, it must be admitted that it is fairly successful in meeting a number of criteria that are required to facilitate understanding by the public and the media — who have adopted it — of events occurring in nuclear facilities. It therefore seemed important to

keep the number of communication tools to a minimum and to comply whenever possible with the logic of the INES when prioritising events involving radiological protection.

To ensure a certain degree of compatibility between the two systems and thereby invest the system proposed with the same strong power of communication, it was decided to retain some of the properties of the INES, particularly:

- Division into **8 levels of severity numbered from 0 to 7**: it appeared essential to use a radiological protection event classification system that had the same number of levels as the INES system in order not to add to the confusion, which would have been quite contrary to what we have set out to do.
- Use of the **same terminology to qualify events**: thus, as with the INES, incidents are taken as being events classified at Level 1 or higher. Accidents are those at Level 4 or above. Events at Level 0 are considered as deviations.
- **Level 2** applicable to all instances **where regulatory limits for exposure to ionising radiation are exceeded**: this criterion is positioned explicitly on the INES and must be at the same level on the radiological protection event scale.

Once these common properties between the two systems have been established, it is recommended that the maximum value obtained using the INES classification system (not taking into account its radiological protection criteria) and the radiological protection scale proposed in this report be used to indicate the severity of events which have consequences for the nuclear safety of installations and result in exposure of workers or members of the public.

4. THE RADIOLOGICAL INCIDENT AND ACCIDENT SEVERITY SCALE

The figure below shows the scale proposed for indicating the severity of events associated with the radiological protection of workers and the public. Section 5 describes the method used to position events on the scale.

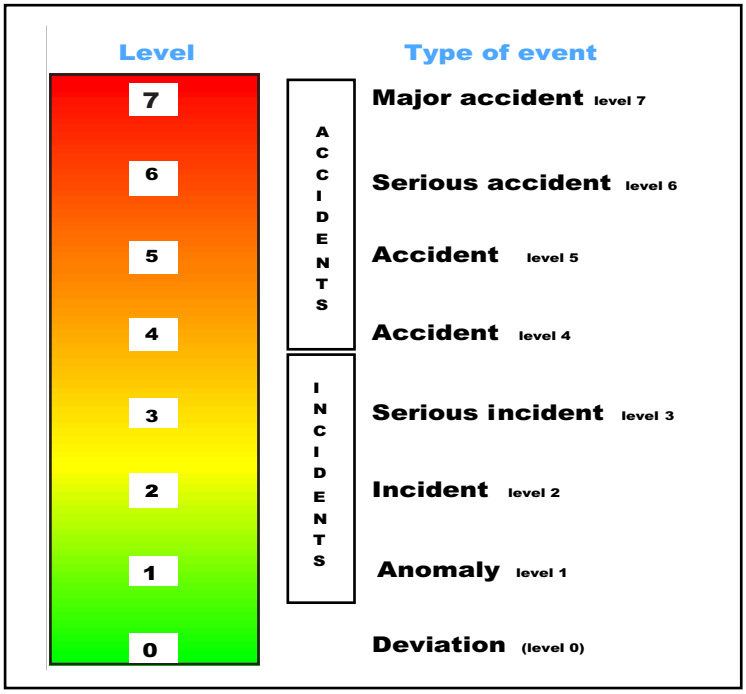


Figure 1. Radiological incident and accident severity scale

- Events classified as Level 0 are known as **"deviations"**; they can be considered as being without consequence as regards radiological protection.
- Events classified as Levels 1 to 3 are **"incidents"**.
  - events classified as Level 1 are known as "anomalies".
  - events classified as Level 2 are known as "incidents".
  - events classified as Level 3 are known as "serious incidents".
- Events classified as Levels 4 to 7 are **"accidents"**.
  - events classified as Level 4 are known as "Level 4 accidents".[5]
  - events classified as Level 5 are known as "Level 5 accidents".
  - events classified as Level 6 are known as "serious accidents".
  - events classified as Level 7 are known as "major accidents".

---

5 The words "Level 4" will be added to differentiate these accidents from the "Level 5" serious accidents.

5. METHOD USED TO DETERMINE THE SEVERITY OF AN EVENT AS A FUNCTION OF THE INDIVIDUAL RADIOLOGICAL RISK FOR A MEMBER OF THE PUBLIC

5.1. Introduction

The proposed system can be used to classify events during which individuals have been exposed to radiation in incident or accident situations.

This section describes the method used to classify events involving members of the **public**. All the classification criteria for other events, for example worker exposure, the exposure of several individuals etc. will be based on the classification for a member of the public using specific severity weighting factors (cf. Section 6). The case of patient exposure will be covered later on (cf.Section 2.2).

Section 5.2 describes the classification method and criteria for events resulting in exposure to ionising radiation and which are likely to lead in the medium or long term to **stochastic effects** in the individuals exposed.

Section 5.3 describes the classification method and criteria for events resulting in exposure to ionising radiation and which are likely to lead in the short or medium term to **deterministic effects** in the individuals exposed.

5.2. Classification criteria for stochastic effects

The individual risk of death, defined as the probability - over an entire lifetime - of a member of the public contracting a **fatal cancer** after being exposed to ionising radiation in an incident or accident situation, has been adopted as the main criterion for establishing a **severity level**[6]. By international consensus, a linear no threshold dose-risk relationship is used to determine this risk as a function of the exposure level.

---

6 Appendix 1 describes the method and tools available for calculating the risk of occurrence of stochastic effects (in this case, fatal cancers) as a function of effective dose, dose rate, organs exposed, age at the time of exposure and gender of the individual exposed. This method is based on existing international consensus and on the recommendations made by the International Commission on Radiological Protection (ICRP).

By definition, and to remain consistent with the INES, the risk associated with the regulatory individual annual dose limit corresponds to a severity level of 2. In France, and the majority of countries, this limit[7] (the sum of the effective doses received by a member of the public) is 1 mSv per year. As our knowledge of the matter stands at present[8], an effective dose of 1 mSv (provided it has been received at dose rates of less than 0.1 Gy/h) corresponds (on average, for the general public[9]), to a lifetime probability of death from cancer of $5x10^{-5}$.

It is commonly accepted (Richter scale, noise scale etc.) that when a risk is increased by a factor of 10, the level on the corresponding severity scale increases by 1. The other severity levels are therefore placed on either side of the severity level of 2 according to a logarithmic graduation (cf. Figure 2). Following this logic, a severity level of 5 is reached when the lifetime probability of death from cancer is 5%, i.e. for an effective dose of the order of 1 Sv.

---

7 Decree no 2002-460 of April 4, 2002 relating to the general protection of the people against the dangers of the ionizing radiations.

8 International Commission for Radiological Protection (ICRP). Publication 60, 1990.

9 In some cases, particularly when children and infants are exposed, it is recommended that a more detailed risk calculation be made, making allowance for the age and gender of the individual exposed. Indeed, average risk coefficients are not suitable for use in all situations (cf. Appendix 1).

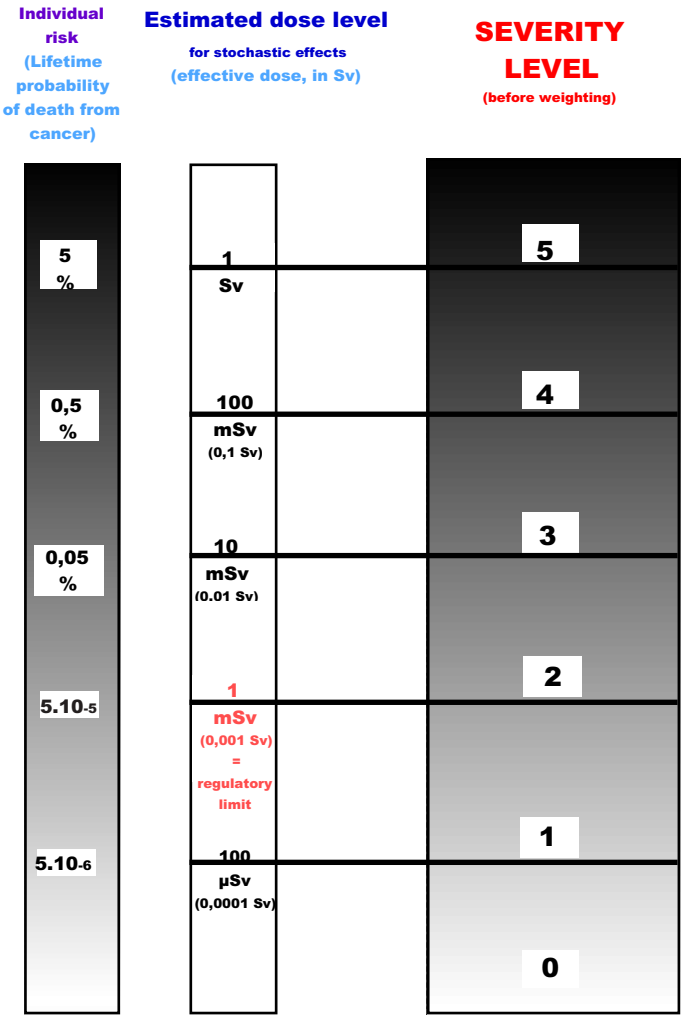


Figure 2. **Determining the severity level for stochastic effects (in the case of exposure of members of the public)**

5.3. Classification criteria for lethal deterministic effects

As in the previous case, the individual risk of death (defined as the probability of a member of the public developing a **lethal deterministic effect**[10] following exposure during the event in question) has been adopted as the main criterion for determining **severity levels**. Deterministic effects are threshold effects, in other words, below a certain dose level, there is no effect. Above the threshold, the probability of occurrence of the

10 Examples of lethal deterministic effects: bone marrow irradiation, lung irradiation, gastro-intestinal syndrome, foetal death.

effect increases according to the sensitivity of individuals to radiation. There are well-known dose-effect relationships for each type of organ: above the threshold, a probability of developing the effect[11] can be associated with each level of exposure of the organ.

Lethal dose 5 (D_5) is the term used for the equivalent dose to the organ (expressed in grays) such that the number of deaths in a uniformly exposed population exposed to dose D_5 is 5%[12]. In terms of severity, a given probability of death is always equally severe, regardless of the cause. Thus, severity level 5 is associated with a 5% risk of death from a stochastic effect (effective dose in sieverts) and to a 5% risk of death from a deterministic effect (dose to the organ in grays, D_5).

Likewise, an event to which an individual was exposed to lethal dose 50 or higher (D_{50} or above) will be given a severity level of 6, since the level of severity increases by 1 when the risk increases by a factor of 10. Figure 3 shows the severity indices as a function of the probability of occurrence of a lethal effect.

The dose levels shown in the charts in Appendix 2 are for information only: indeed, whatever the estimated dose, a clinical observation of the effect prevails over the probability of occurrence of the effect related to the dose, and hence the severity index relies on clinical observation. Therefore, an observed lethal effect automatically positions the event at a severity level of 6.

---

11 Appendix 2 describes the method and tools available for calculating the risk of occurrence of deterministic effects (lethal and non-lethal) as a function of absorbed dose, dose rate and the organs or biological tissues that have been irradiated. The recommended method is based on one of the most recent publications in the field (NRPB, 3)

12 The survival rate corresponding to this dose would therefore be 95%. This dose level depends essentially on the irradiated organ or tissue and on the dose rate (see Appendix 2).

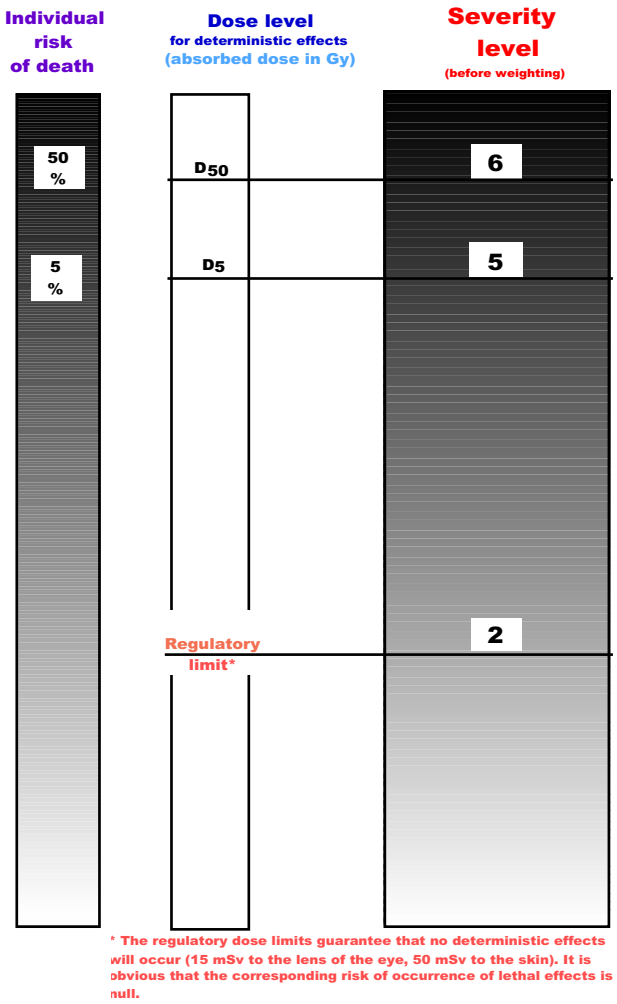


Figure 3. Determining the severity level for lethal deterministic effects (in the case of exposure of members of the public)

5.4. Weighting for non-lethal deterministic effects

Events likely to result in non-lethal deterministic effects are less severe than those likely to lead to lethal deterministic effects.

As in the case of lethal deterministic effects, the dose-risk relationships are well known. Therefore, for each type of effect, doses D_5 and D_{50} to organs, resulting in a probability of developing the effect of 5% and 50% respectively, are known.

The charts in Appendix 2 can easily be used for each type of event to determine the probability of occurrence of the effect on the basis of measurement or estimation of the absorbed dose and the dose rate.

The severity level is then obtained using Figure 3, after which a sub-weighting factor is applied to make allowance for the observed or probable effect. It then has to be determined whether the effect is disabling or not. Indeed, just as lethal effects are considered more severe than non-lethal ones, so disabling effects are considered as more severe than those which are not.

Non-lethal disabling effects[13] are irreversible effects that seriously affect bodily functions. These consequences are disabling for the exposed individual and severely affect his physical behaviour, his bodily functions and/or his relations with other individuals.

The severity level for non-lethal disabling effects is equal to the severity level obtained by applying the system described in Section 5.3 for lethal deterministic effects, minus 1.

Non-lethal non-disabling effects[14] are effects that are generally found to be reversible. However, these types of effects must be handled cautiously since in some cases they can precede the appearance of other, far more serious effects (prodromal syndrome).

The severity level for non-lethal non-disabling effects is equal to the severity level obtained by applying the system described in Section 5.3 for lethal deterministic effects, minus 2.

---

13 Examples of non-lethal disabling effects (according to the classification adopted): temporary or definitive ovogenesis failure, temporary spermatogenesis failure, cataract, pulmonary fibrosis, different types of necrosis, teratogenic effects such as severe mental handicap or microcephalus following irradiation of the foetus or embryo.

14 Examples of non-lethal non-disabling effects (according to the classification adopted): vomiting, diarrhoea, hypothyroid, thyroiditis, burns and erythema.

6. SEVERITY WEIGHTING AS A FUNCTION OF OTHER CRITERIA

All other exposure events are classified using a system of sub or excess weighting of the scale described in the previous section for exposure of the public in incident and accident situations.

6.1. Worker exposure

To classify events resulting in exposure of workers[15] in an incident or accident situation (i.e. exposure that was not planned or foreseeable at the dose levels received), the system proposed is equivalent to that described for classifying events involving members of the public, except that all the levels are one lower.

Given the logarithmic nature of the scale proposed, this is tantamount to positioning acceptability of the radiological risk at a level ten times higher for workers than for members of the public. This factor ten is often interpreted, in risk-perception studies, as the difference between a risk that is chosen (by workers) and suffered (by the public). This interpretation is not strictly appropriate in the context of events occurring in incident and accident situations. Nonetheless, this logic generally determines society's view of industrial risks and ICRP relied on that rationale to set, in its Recommendation 26, annual dose limits of 50 mSv for the workers and 5 mSv for the public (these recommendations for regulatory limits have been modified since).

Figure 4, overleaf, summarises the method used to establish the severity indices for events involving workers.

15 "Workers" are taken as being those who, in the normal course of their work, are required to handle, transport or be exposed to the radioactive source to which they were exposed during the event in question.

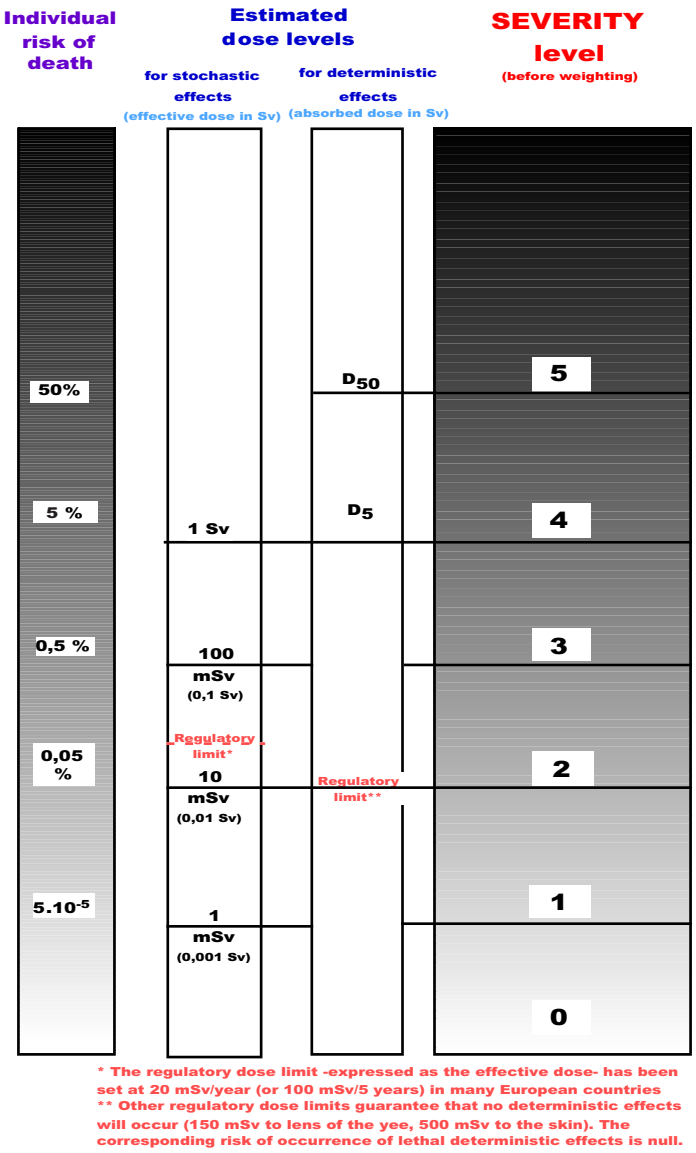


Figure 4. Determining severity levels (in the case of worker exposure)

Special case: When the 1 to 10 mSv dose received during the event also causes the annual regulatory limit (20 mSv) to be exceeded[16] because of doses received by the exposed worker in the past, the severity level (initially 1) increases to 2. This weighting ensures consistency between the scales used for workers and members of the public and between the proposed system and the INES.

6.2. Collective exposure

16 Draft decree relating to the protection of workers against the dangers of ionising radiation (approved at the interministerial meeting held on 2 August 2002).

When several individuals are exposed, an excess weighting factor is applied that depends on the number of persons exposed:

- an excess weighting factor of 1 is applied to the initial severity level when more than 10 individuals have received doses within the same risk range.
- an excess weighting factor of 2 is applied to the initial severity level when more than 100 individuals have received doses within the same risk range.

The excess weighting factor is only applied for severity levels greater than or equal to 2 (i.e. higher than the regulatory annual dose limits). Furthermore, the level of severity can never be higher than Level 7 (major accident), which could limit application of the excess weighting rule in some cases.

6.3. Combined exposure (members of the public + workers)

When members of the public and workers are exposed simultaneously, the event is classified using the two systems described above. Any weighting factors required to make allowance for collective exposure of either of the two types of population shall be applied.

The maximum severity level obtained by the two classification systems (relating to the public and workers) shall be used for communication purposes.

6.4. Internal exposure

Internal exposure (by ingestion, inhalation or transcutaneously) is not dealt with in any special way (for example there is no excess weighting). However, it is difficult to assess internal doses quickly since the results of biological assays are often required. It will no doubt be necessary to use modelling software to assess this type of exposure so that events can be quickly classified on the scale proposed in this report.

6.5. Potential exposure

Some events not resulting in significant exposure could have done so had the circumstances been slightly different while remaining completely realistic. These are known as potential exposure situations. If an operator, or the safety authority, considers that the probability of such a situation occurring is sufficiently high, it is recommended

that the doses that could have been received in these circumstances be assessed (by calculation and using appropriate models). Once these doses have been assessed, it is possible to have them correspond to a level of severity using the scales described in Section 5. But since the exposure did not really occur, sub-weighting factors are applied. The severity level may be lowered by one or two levels, at the discretion of the radiological protection authority.

When indicating the severity level, the potential nature of the exposure relating to the event in question should be clearly specified.

6.6. Exceeding limits other than dose limits

As soon as a regulatory limit other than a dose limit has been exceeded during an event (for example a surface contamination limit for packages, a dose rate limit in a classified area etc.), an excess weighting factor of 1 is applied to the initial severity level.

Excess weighting is possible for severity levels of less than 2 (≤ 1).

6.7. Shortcomings in radiological protection culture

Whenever the radiological protection authority deems it appropriate, it can increase by one the severity level of an event whose severity level is less than 2 (≤ 1) if it considers there are shortcomings in the radiological protection culture.

7. EXAMPLES

This section describes thirteen events that actually occurred and for which use of the radiological protection scale proposed in this report results in classification levels covering all eight severity communication levels.

7.1. Examples of Level 0 events (deviations)

Example 1. 2 September 2002, France. While three welders were replacing an air extraction system on a radioactive sample pneumatic transfer system, which also provided containment and biological shielding of operators, with another more powerful device, their hands and feet were contaminated when they opened a filter housing and removed a HEPA filter. They were trying to repair a faulty weld using argon scavenging. Medical examinations revealed nothing of any significance.

Category of persons exposed: workers
Severity level corresponding to the doses received: 0
No radiological protection culture shortcomings evident (no excess weighting)

➠ Level on radiological protection scale: 0

➠ Type of event: **Deviation**.

Example 2. 1997, France. – In the curietherapy unit of a large hospital, when five irridium-192 wires were being removed from a patient (each 7 cm long with an activity of 37 MBq per centimetre), one of the wires was found to be missing. A radiation meter was used to search the entire hospital and it was finally found in a bag of dirty linen waiting to be sent to the laundry. A nursing auxiliary was probably irradiated when changing the patient's pillowcase, receiving a very low dose of less than 50 microsieverts.

Category of persons exposed: worker or the public (to be determined depending on the qualifications and training of the person exposed to the risks run in the course of her work)
Severity level corresponding to the doses received: 0
No radiological protection culture shortcomings evident (no excess weighting)

➠ Level on radiological protection scale: 0

➠ Type of event: **Deviation**.

7.2. Examples of Level 1 events (anomalies)

Example 3. 20 August 2002, France. – Detection of a hot spot on the outside of a container full of slightly radioactive material, sent from one nuclear power plant to another for re-use. On arrival at the power plant, surface contamination of 850 Bq/cm^2 was measured. This had not been detected at the power plant from which the material was sent, despite the fact that radiological checks had been carried out. Neither the personnel nor any members of the public were contaminated. For information, the French regulations stipulate a limit of 4 Bq/cm^2 for this type of package.

Category of persons exposed: workers and perhaps members of the public (during transport)
Severity level corresponding to the doses received: 0
Regulatory radiological protection limit exceeded (excess weighting of +1)

➠ Level on radiological protection scale: 1

➠ Type of event: **Level 1 anomaly**.

Example 4. 28 August 2002, France. – While handling a 148 MBq solution of yttrium-90 containing strontium-90 impurities, an operator, unable to complete the operation using the equipment available (a syringe provided with a filtering membrane and biological shielding), decided to examine the tool and removed it from its protective casing. When he grasped the filtering membrane, he received an equivalent dose of 147 mSv to his left hand. For information, the French regulatory limit for this type of exposure is 500 mSv/year.

Category of persons exposed: worker
Severity level corresponding to the doses received: 0
Evident shortcoming in radiological protection culture (excess weighting +1)

➠ Level on radiological protection scale: 1

➠ Type of event: **Level 1 anomaly**.

7.3. Examples of Level 2 and 3 events (incidents and serious incidents)

Example 5. 2001, France. – During a crystallography experiment, an operator activated the safety devices of the apparatus to make a number of adjustments when the beam was on (4000 Gy/h at 40 kV and 20 mA). A second operator, who did not know that the apparatus was energised, quickly passed his hand through the beam to warn the other operator that the beam and the sample being studied were not properly aligned. The maximum exposure duration was estimated at one second. The maximum dose (to the extremities) was estimated at 360 mSv.

Category of persons exposed: member of the public (trainee)
Severity level corresponding to the doses received: 2 (regulatory limit for members of the public exceeded)
Number of persons exposed < 10 (no excess weighting)

➠ Level on radiological protection scale: 2

➠ Type of event: **Level 2 incident**.

Example 6. 1995, France. - An operator working in a decontamination unit of a plant was cleaning a gauge used to measure the density of washing solutions due to be released into the environment. Despite the warning notices that the object was radioactive and dangerous (it contained a 7.4 GBq caesium-137

source), he disassembled the container and took out the source and held it in his hand and also removed the collimator tube which he took to another facility to be cleaned with compressed air. The French Curie Institute estimated that the dose received by the hand during the accident was more than 25 Gy (resulting in erythema followed by oedema and finally a lesion 5 cm in diameter with exudative epidermitis), with a whole body effective dose of almost 200 mSv.

Category of persons exposed: worker
Severity level corresponding to the doses received: 5 (deterministic effect observed) –2 (non-lethal non-disabling effect considered by doctors to be reversible) = 3
Note. A severity level of 3 is also obtained if the whole body effective dose is considered.
Number of persons exposed < 10 (no excess weighting)

➠ Level on radiological protection scale: 3

➠ Type of event: **Level 3 Serious incident**.

Example 7. 1982, France. – During a gammagraphy inspection, the source-holder cable became detached when the source was being put back into the projector (a sealed irridium-192 source with an activity of around 850 GBq). After some time, the operators noticed that the source was stuck in the hose and managed to release it by shaking the hose. The film badges of the three exposed operators were developed without delay. The whole body dose received by one of the operators was estimated at 155 mSv; the two others were exposed to a lesser extent (less than 5 mSv). Subsequent biological dosimetry revealed chromosomal aberrations and the operator developed lymphopenia.

Category of persons exposed: workers
Severity level corresponding to the doses received: 3
Number of persons exposed < 10 (no excess weighting)

➠ Level on radiological protection scale: 3

➠ Type of event: **Level 3 Serious incident**.

Example 8. 11 March 1999, France. – A technician in the industrial safety and radiological protection department of a nuclear power plant entered a prohibited area without authorisation (this is an area where the equivalent dose rate is likely to exceed 100 mSv/h and to which access is granted in exceptional circumstances in line with special procedures and authorisations that severely limit the stay time). The area was located under the vessel of the reactor which was shut down for maintenance. He entered the reactor pit to retrieve some maintenance tools and for three minutes, he was in the vicinity of a number of thimbles, the highly radioactive measuring instruments that had been installed to check for reactor vessel leakage during fuel unloading. As he was leaving the reactor pit, he realised (from his electronic dosimeter) that he had just received a dose of more than 340 mSv. When his passive dosimeter was developed, it was confirmed that he had received a dose of around 300 mSv.

Category of persons exposed: worker
Severity level corresponding to the doses received: 3 (*)
Number of persons exposed < 10 (no excess weighting)

➠ Level on radiological protection scale: 3

➠ Type of event: **Level 3 Serious incident**.

Reminder: the French safety authorities classified this event as Level 2 on the INES.

Note(*): in this case, the fact that the dose rate was higher than 0.1 Gy/h did not affect the risk range as it could have done in other cases. When the dose rate is higher than 0.1 Gy/h, the risk of fatal cancer is twice as high as the risk resulting from the same dose received at a lower dose rate.

7.4. Examples of Level 4 to 6 events (accidents and serious accidents)

Example 9. 7 January 2002, France. – Incident during the transfer of radioactive material between Sweden and the United States involving a package with an abnormally high dose rate (4 mSv/h at 25 metres). It was discovered that the end caps of two tubes containing radioactive pellets of irridium-192, with an activity of 366 TBq, were loose. The handling staff underwent medical examinations and it was found that two of them had received doses of the order of 15 mSv and that the package had been faulty when it passed through Charles de Gaulle airport (it is thought the driver received a dose of 3.4 mSv). Six weeks later, the additional results requested by the authorities showed that one of the handlers had, in fact, received a dose of 100 mSv.

Category of person exposed: public (untrained workers not in the habit of being exposed)
Severity level corresponding to the doses received: 3
Number of persons exposed < 10 (no excess weighting)

➠ Level on radiological protection scale: 3

➠ Type of event (provisional): **Level 3 serious incident**.

The severity level was re-assessed one month after the event and set at almost 4 (the risk corresponding to the value of 100 mSv is on the borderline between Levels 3 and 4; to decide on the true level, further details on exposure duration, measurement accuracy etc. will be required).

➠ Probable level on radiological protection scale (after requalification): 4

➠ Type of event (final): **Level 4 accident**.

Reminder: the Swedish safety authorities classified this event as Level 3 on the INES.

Example 10. 30 September 1999 – Tokaï-Mura, Japan. A criticality accident occurred in a uranium conversion plant, in a tank containing a nitric acid solution of uranium enriched to 18.8% with isotope 235. It was caused by insufficiently qualified workers carrying out unplanned manual operations (transfer of solutions using 10 litre buckets). During the first power peak, the three operators close to the tank received doses that were initially estimated at 17, 10 and 3 Gy, then revised to 9, 5 and 1.2 Gy (the doses were estimated after the event because the operators were not wearing dosimeters). Criticality continued for around 20 hours before it was properly brought under control by draining the water that cooled the tank from the outside and which acted as a neutron reflector. A total of 24 persons were required to bring the accident under control and all received doses of between 1 and 48 mSv. Estimates showed that there were few consequences for the environment and that they were mainly limited to direct irradiation by the rays from the tank. The most highly exposed operator (who was holding the funnel into which the buckets were poured) died on 21 December, two months after the accident, despite receiving highly advanced medical care. The second, who was originally thought to have "a reasonable chance of survival" died in April 2000.
Category of persons exposed: workers

Severity level corresponding to the doses received: 5, index relating to the deterministic effects observed in the three individuals exposed*; the index is less than 3 for the individuals who brought the situation under control (in their case, there is absolutely no certainty that the doses were "controlled", given the wide disparities in the doses received).
Number of persons exposed < 10 (no excess weighting)

➠ Level on radiological protection scale: 5

➠ Type of event: **Level 5 accident**.

Reminder: the Japanese safety authorities classified this event as Level 4 on the INES.

Note(*): an event occurring under similar circumstances but resulting in the semi-lethal exposure of more than 10 workers would be qualified as a **Level 6 serious accident**.

> *Example 11. 27 February 2001 – Bralystock, Poland. After a power outage had caused a linear accelerator to suddenly stop operating, irradiation treatment of five patients with breast cancer (of which four had undergone the ablation of a breast) was resumed without recalibration of the apparatus. The alert was raised when two patients complained of a burning sensation after irradiation. The doctor then discovered that the dose rates were ten to twenty times higher than intended. Over the next months, the five patients developed debilitating deep necrosis, two of them exhibiting total destruction of the tissue down to the pericardium. The lesions observed were the most serious in these two patients, apparently indicating progressive deterioration of the beam. The dose was estimated at above 150 Gy. Without the specialized care that they received at the Curie Institute, they would probably both have died. In late 2002, no prognosis of the life expectancy in the medium or long term could be given for four of the five women.*

Category of persons exposed: members of the public (patients)
Severity level corresponding to the doses received: 5 (near-lethal dose for at least two of the patients, body surface less than 30%, with chance s of survival after treatment)
Number of persons exposed < 10 (no excess weighting)

➠ Level on radiological protection scale: 5

➠ Type of event: **Level 5 accident**.

Note: The medium and long term prognosis for two of the patients is uncertain, and the accident would be re-classified as a **Level 6 serious accident** in the event either dying as a direct result of the irradiation that they suffered.

7.5. Examples of Level 7 events (major accidents)

Example 12. September 1987, Goiânа, Brazil – Two rag-and-bone men went into an abandoned building that used to be a private radiotherapy clinic; they found an old piece of apparatus, took it apart, removed the lead cap and took it home. From the apparatus they removed a capsule containing 20 g of caesium chlorate in powder form. They opened it, thereby releasing the caesium-137 (with an activity of 51 TBq). The lead capsule containing caesium that had not been dispersed immediately was sold to a scrap metal dealer. The luminescent blue powder attracted the attention of family members and neighbours and was passed from one to the other, some even rubbing it against their skin. Seventy five days after the source had been discovered by the rag-and-bone men, and with at least four people dead from the effects of irradiation, the Brazilian health authorities began examining almost 112,000 people: 249 had serious

internal and/or external contamination and 49 had to be admitted to hospital, including 21 in intensive care. Three other people died in the next few months. One person had to be amputated. Six hundred people are still having regular medical check-ups.

Category of persons exposed: public
Severity level corresponding to the doses received: 6
Number of persons exposed: > 100 including more than ten at doses that were at least semi-lethal (excess weighting +1)

➠ Level on radiological protection scale: 7

➠ Type of event: **Major accident Level 7**.

Reminder: the Brazilian safety authorities classified this event as Level 7 on the INES.

Example 13. 26 April 1986 – Chernobyl, Russia. In the days and months following the explosion of the reactor, 32 of the emergency workers died and more than 100 others were found to be suffering from lesions caused by irradiation. Among the general public, more than 2000 cases of thyroid cancer have been diagnosed in children who were exposed at the time of the accident and if this trend continues, more cases could come to light in the next few decades (source: United Nations Scientific Committee on the Effects of Atomic Radiation 2000 report). Statistical calculations estimate that the accident could result in several "liquidators" dying from cancer (source: French Institute for Radiological Protection and Nuclear Safety). Of the 600,000 liquidators (who have to be considered as members of the public in view of their ignorance of the risks involved), around 10% received doses of more than 250 mSv and 20% doses of between 100 and 165 mSv.

Category of persons exposed: workers and the public

Severity level corresponding to the doses received: 5
Number of persons exposed: > 10 (excess weighting +1)
Level on radiological protection scale: 6

Severity level corresponding to the doses received by members of the public: 6
Number of persons exposed: > 100 (excess weighting +1)
Level on radiological protection scale: 7

➠ Level on radiological protection scale: 7*

*maximum value between the level obtained for workers and that obtained for members of the public

➠ Type of event: **Major Level 7 accident**.

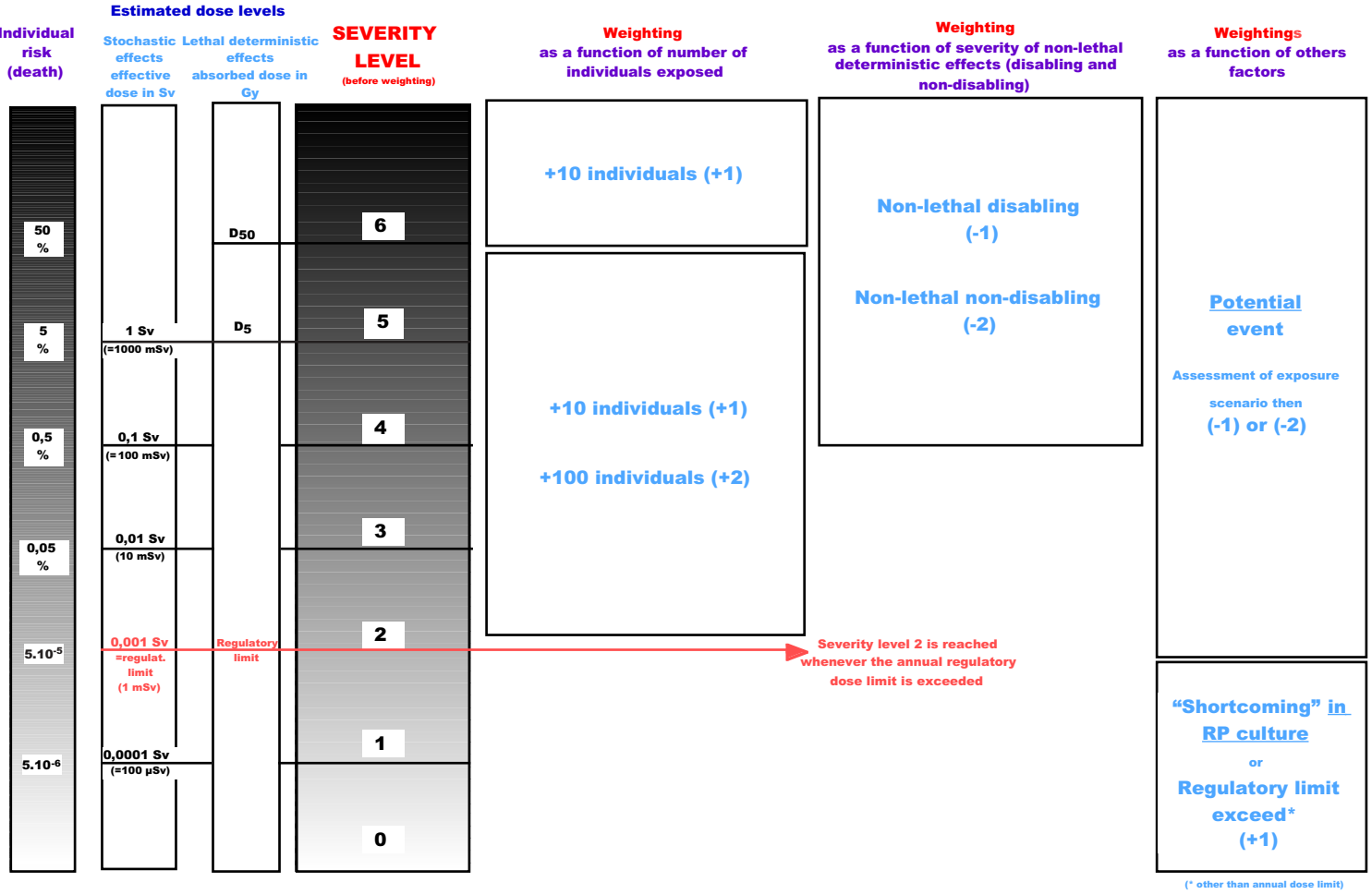
Reminder: this event was classified as Level 7 on the INES.

APPENDICES

Appendix 1: Method and tools available for calculating the risk of occurrence of **stochastic effects** as a function of dose, dose rate, organs exposed, age at time of exposure and gender.

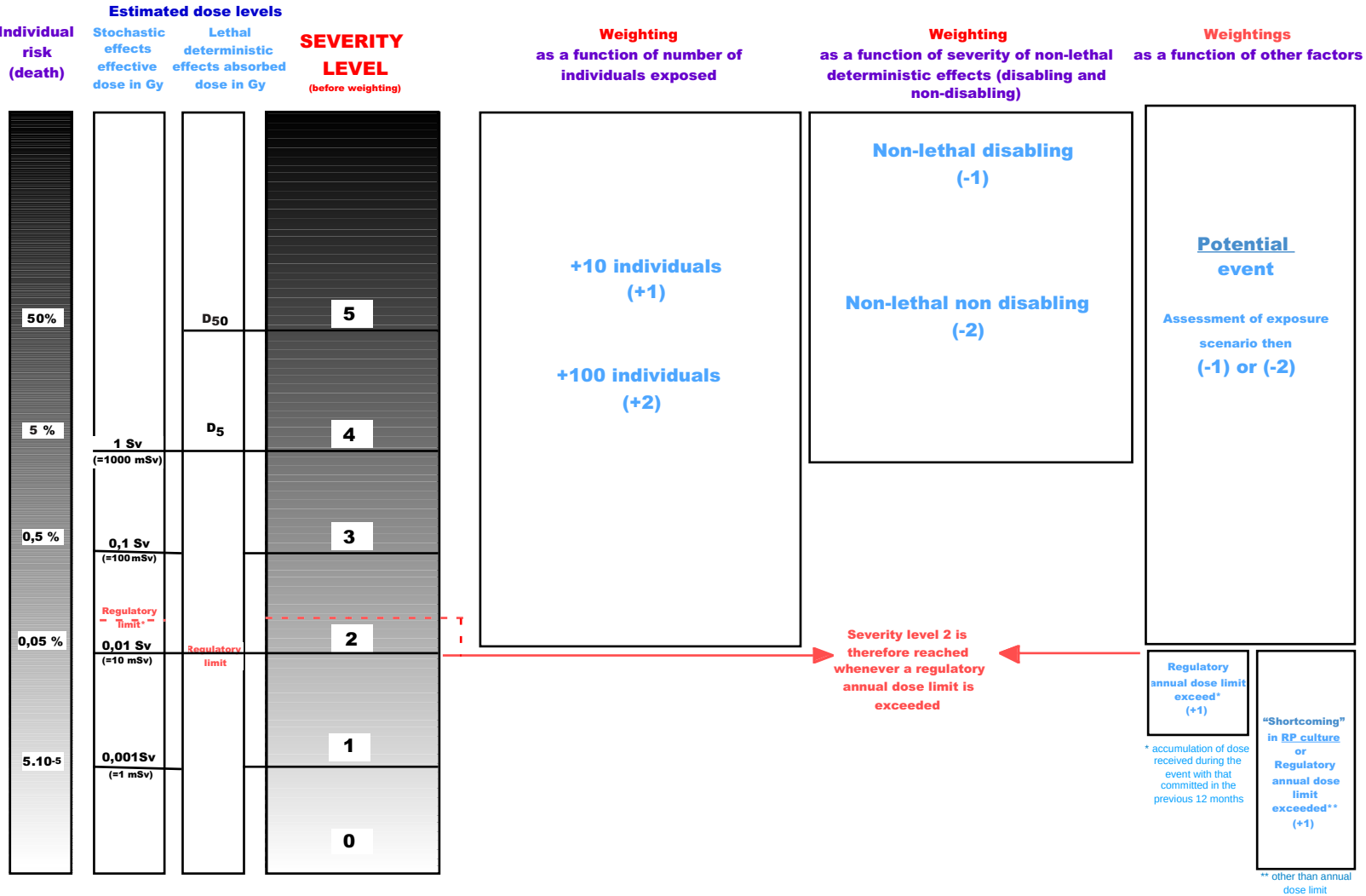
Appendix 2: Method and tools available for calculating risk of occurrence of **deterministic effects** as a function of dose and dose rate (National Radiological Protection Board 1996 model).

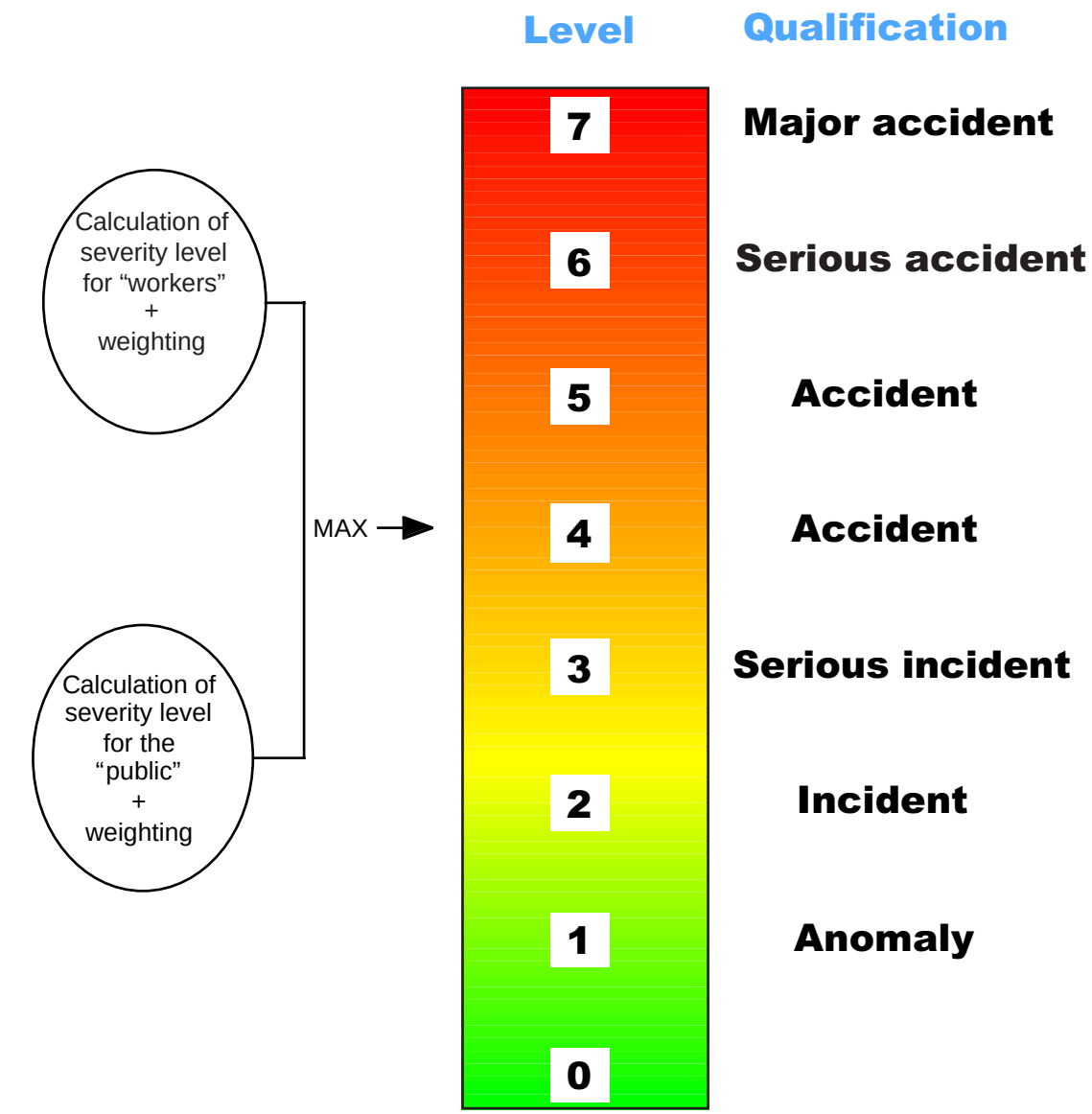
CLASSIFICATION OF EVENTS AFFECTING MEMBERS OF THE PUBLIC*



(*) In most cases, the severity level for an event involving workers can be deduced using this chart and reducing the severity level obtained by 1

CLASSIFICATION OF EVENTS AFFECTING WORKERS




Level
Qualification
7
Major accident
6
Serious accident
5
Accident
4
Accident
3
Serious incident
2
Incident
1
Anomaly
0
Calculation of severity level for "workers" + weighting
Calculation of severity level for the "public" + weighting
MAX

REPORT N° 276

PROPOSED CLASSIFICATION SCALE FOR RADIOLOGICAL INCIDENTS AND ACCIDENTS

APPENDIX 1

Method and tools available for calculating the risk of occurrence of stochastic effects as a function of dose, dose rate, organs exposed, age at time of exposure and gender

---

Pascal CROÜAIL, David COLLIN, Christian LEFAURE

CONTENTS

LIST OF TABLES

LIST OF FIGURES

APPENDIX 1

METHOD AND TOOLS AVAILABLE FOR CALCULATING THE RISK OF OCCURRENCE OF STOCHASTIC EFFECTS AS A FUNCTION OF DOSE, DOSE RATE, ORGANS EXPOSED, AGE AT TIME OF EXPOSURE AND GENDER

STOCHASTIC: "phenomenon or process that is due in part to chance"

The aim of this appendix is to outline the international consensus that acts as a basis for estimating stochastic risks associated with exposure to radiation and to describe the tools used to estimate them as simply as possible once doses are known or have been estimated.

1. ASSESSING THE RISK OF OCCURRENCE OF STOCHASTIC EFFECTS

1.1. Origin and nature of stochastic effects

The carcinogenic effects are caused by reactions between the ionising radiation and the DNA molecules in the cells. These reactions lead to mutations if the enzyme repair systems fail to repair the DNA damage or repair it badly; these mutations may cause cancer to develop. The process leading from the initial reaction to the occurrence of cancer is extremely long and complicated. Laboratory and epidemiological studies have shown that the first cases of radiation-induced cancer occur several years (or even a decade) after exposure and continue to occur in a very marked manner several decades after exposure.

These carcinogenic effects are of a probabilistic nature (the term stochastic is also used) since within a uniformly exposed population, it is impossible to predict which individuals are likely to develop a radiation-induced form of cancer. As we understand it today, the situation is as follows:

- During exposure to ionising radiation, energy is deposited at random in the cell, organ or body as a whole,

- DNA strands are not automatically broken when energy is deposited,
- And lastly, the repair and mutation phenomena occur at random, as does multiplication of mutated cells.

Furthermore, the effects produced by exposure to ionising radiation are not identifiable, in other words our current level of knowledge does not allow us to differentiate between one radiation-induced cancer and another cancer, except in extremely rare cases.

1.2. Assessing the risk of occurrence of stochastic effects

While laboratory studies of cell lines and animals are important for understanding the mechanisms whereby stochastic effects occur, in no way, as the situation stands at present, can they be a basis for quantitative assessment of the risk of a human being developing radiation-induced cancer. The scientific discipline that proved the existence of this type of effect is known as epidemiology[1]. It has revealed statistically significant excesses in the number of deaths by cancer in exposed populations compared to non-exposed ones.

1.2.1. Epidemiology and its limitations

Epidemiology in its present form has proved the existence of stochastic effects in populations who have received what are known as "flash[2]" doses of more than 100 mSv[3] to the whole body (as regards this issue, see notably [Wingspread Conference, 1997], [Arlie Conference, 1999], [Pierce, Preston, 2000]). On the other hand, because of the intrinsic limitations of the statistical tools on which epidemiology is based, it is not possible to prove the existence of such effects at lower doses with any certainty.

---

1 The major epidemiological studies available concerning exposure to ionising radiation focus on the survivors of Hiroshima and Nagasaki, patients who have received radiotherapy and curietherapy treatment and certain populations of exposed workers (notably miners exposed to radon).

2 i.e. received over a very short period.

3 In the sixties, the proof was only statistically significant above 1 Sv; in the seventies, it was significant at 500 mSv and nowadays it is significant above 100 mSv. In 50 years, the uncertainty threshold has been reduced by a factor of ten.

Quantitative assessment of the probability of an individual developing cancer is based on the use of models. Predictive assessment of the risk for a population is based on:

- Study of the excess risk of death from cancer associated with exposure in the exposed population,
- Fitting of the "exposure-risk" models to the population observed. These models are derived directly from epidemiological data in precise demographic contexts,
- Application of the model to other exposure situations (transfer and extrapolation of risk).

Contrary to what happens with deterministic effects (see Appendix 2), the severity of stochastic effects is independent of the dose received (Figure 1), but the probability of occurrence of the effects increases as the dose increases (Figure 2).

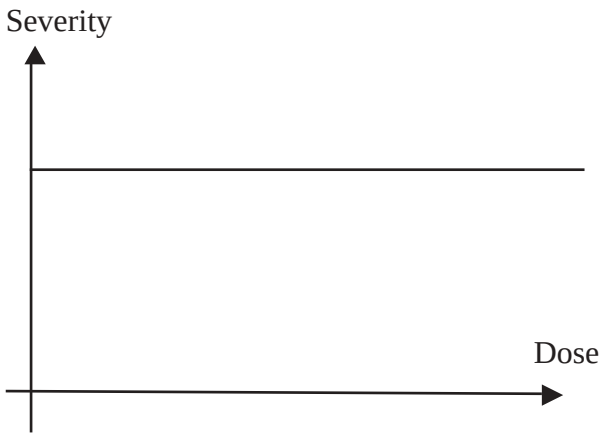


Figure 1. Variation in severity of stochastic effects as a function of dose

For stochastic effects, given the lack of statistically significant data on excess incidences of cancer at low doses (see above), the cautious assumption is made that there is no lower dose limit below which no effects could occur.

For most types of cancer, the most probable dose-risk relationship is either a linear relationship or a linear quadratic relationship (see tables 3(a), (b), (c) and (d) at the end of this appendix). Figure 2 shows the case of linear quadratic relationships.

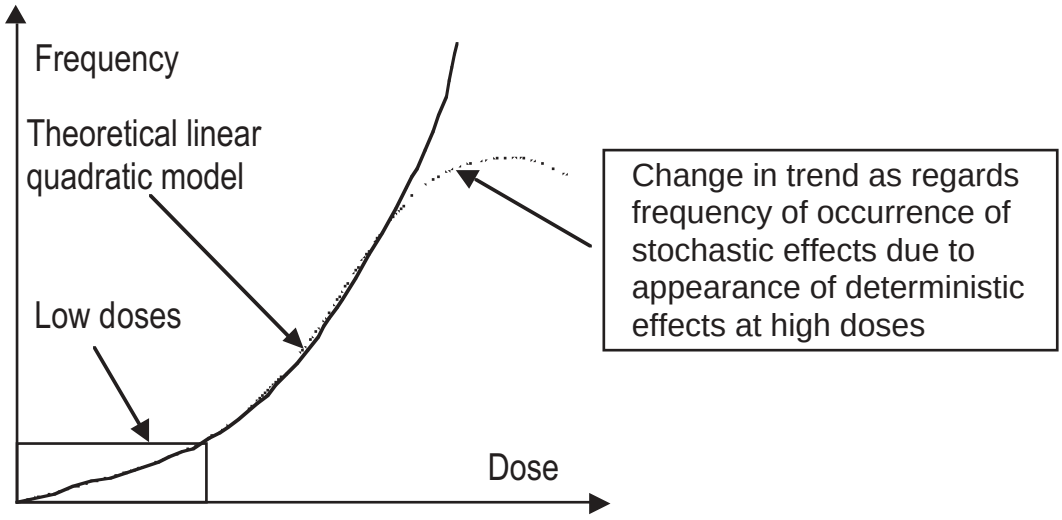


Figure 2. Linear quadratic variation in frequency of occurrence of effects versus dose

At low doses, the relationship corresponds to the linear part of the linear quadratic curve. Below 100 mSv, the curve corresponds to extrapolation of the statistically significant adjustment made for higher doses.

1.2.2. The dose-effect relationship of the International Commission on Radiological Protection (ICRP)

The model used by the ICRP[4] to manage radiological risks had to be easy to use. It is therefore a general model bringing together all possible types of radiation-induced cancer for a reference worldwide population[5] and does not differentiate between the two sexes. The dose-risk relationship proposed corresponds to a whole body exposure.

4 The model is based to a large extent on the 1998 publications of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR).

5 In reality there are five reference populations: Japan, Puerto Rico, United States, United Kingdom and China.

Furthermore, the ICRP, again with a view to risk management, felt it necessary to divide exposed populations into two broad categories: workers aged between 20 and 64 and the population as a whole, i.e. the general public where all ages are represented (0 to 90 years). For this reason, it proposes two risk coefficients to make allowance for the difference.

Lastly, the ICRP makes allowance for the effect of dose rate. Indeed, the UNSCEAR publications estimate that the risk at low doses received at low dose rates is 2 to 10 times lower than the risk at high doses received at high dose rates. For practical reasons and in the interests of conservatism, the ICRP, like most national and international bodies, recommends applying a reduction factor or **DDREF**[6] **of 2** when calculating the radiological risk associated with doses of less than **0.2 Gy** or a dose rate of **0.1 Gy/h**. At low doses and dose rates, this factor corrects the linear coefficient derived from observation of the reference population.

Thus the ICRP obtains four coefficients depending on whether workers or the public are exposed and whether the doses and dose rates are low or not (see Table 1).

Table 1. Lifetime probability of developing fatal cancer expressed as a percentage per sievert (ICRP Publication 60)

Exposed population	**High dose** (>200 mSv) **AND/OR High dose rate** (> 100 mGy/h) % per Sv	**Low dose** (<200 mSv) **AND Low dose rate** (< 100 mGy/h) % per Sv
Workers	8.0	4.0
General public	10.0	5.0

* The ICRP also introduces the risk of occurrence of non-fatal forms of cancer and the risk of genetic effects; these risks are proportional to the risk of fatal forms of cancer since they also have a linear no-threshold relationship with dose. Only the coefficients for the risk of exposed individuals developing fatal forms of cancer have been used here since they suffice to determine the severity levels in the classification system proposed.

6 Dose and Dose Rate Effectiveness Factor.

1.2.3. Other models and radiological risk variation factors

Whenever more detailed information is available and the risk for one or more individuals has to be determined more accurately, the basic models described in the UNSCEAR, BEIR or even NRPB publications should be used. These publications summarise all the existing models. The models are based on different epidemiological studies for different types of cancer.

One of the basic hypotheses worth mentioning is the fact that to estimate the excess risk of exposure-induced death, the model can:

- Either estimate a relative excess risk (the excess risk is expressed as a percentage of the "natural" mortality rate due to cancer in the country in question for a given dose level),
- Or estimate an absolute excess risk (the excess risk is the number of incidences of cancer to be added to the "natural" mortality rate due to cancer in the country in question for a given dose level).

The majority of the up to date existing models use the relative excess risk method.

We shall not describe all the models here, but the four tables at the end of the appendix summarise the major characteristics of the models published most recently.

However, it is worth indicating the impact of certain parameters on the dose-risk relationship, namely:

- the types of organs exposed[7] (particularly if exposure is not uniform throughout the body) which result in different cancer areas,
- age at the time of exposure,
- and gender.

Taking the most recent UNSCEAR model, published in 2000, the two charts below (Figures 3 and 4) clearly show the impact of these three factors.

---

7 Radiation-induced cancers include solid tumours and leukaemia. The results and observations of epidemiological studies show that the shape of the dose-effect curve varies as a function of the type of cancer. Furthermore, as regards solid tumours, it has been shown that the dose-effect relationship varies as a function of the cancer area (colon, lung, thyroid etc.).

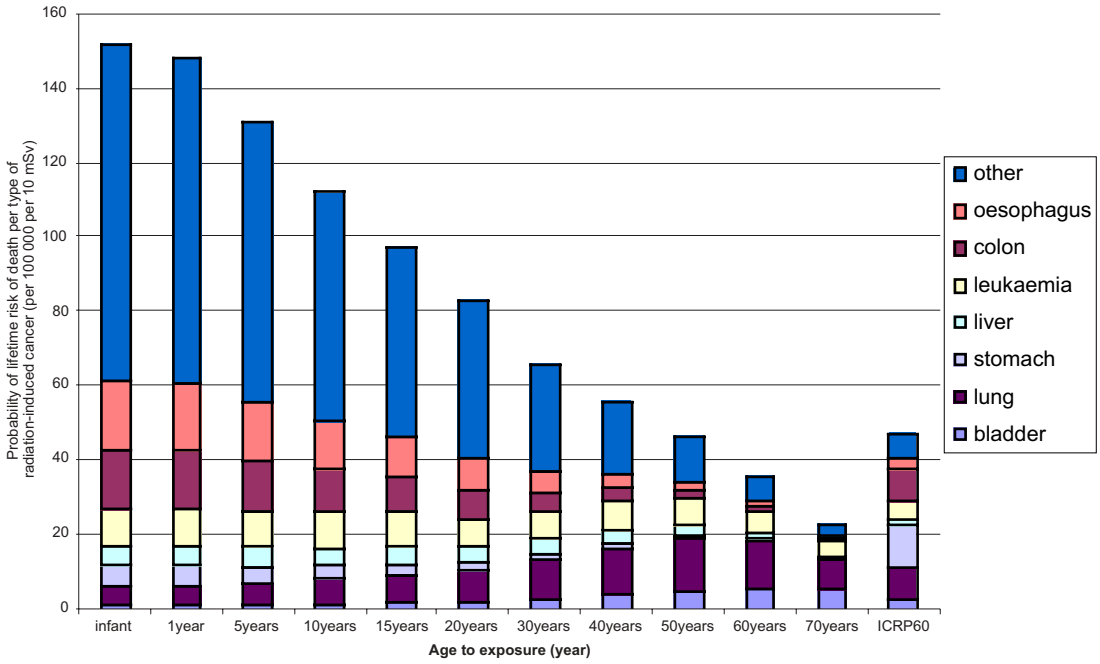


Figure 3. **Cumulative bar charts of lifetime risk of death per age to exposure and per type of radiation-induced cancer (UNSCEAR 2000 model). *For men***

By way of comparison, the values adopted in ICRP Publication 60 are shown; demographic data, France 1994; "equivalent dose to each organ" equal to 10 mSv and use of a DDREF of 2.

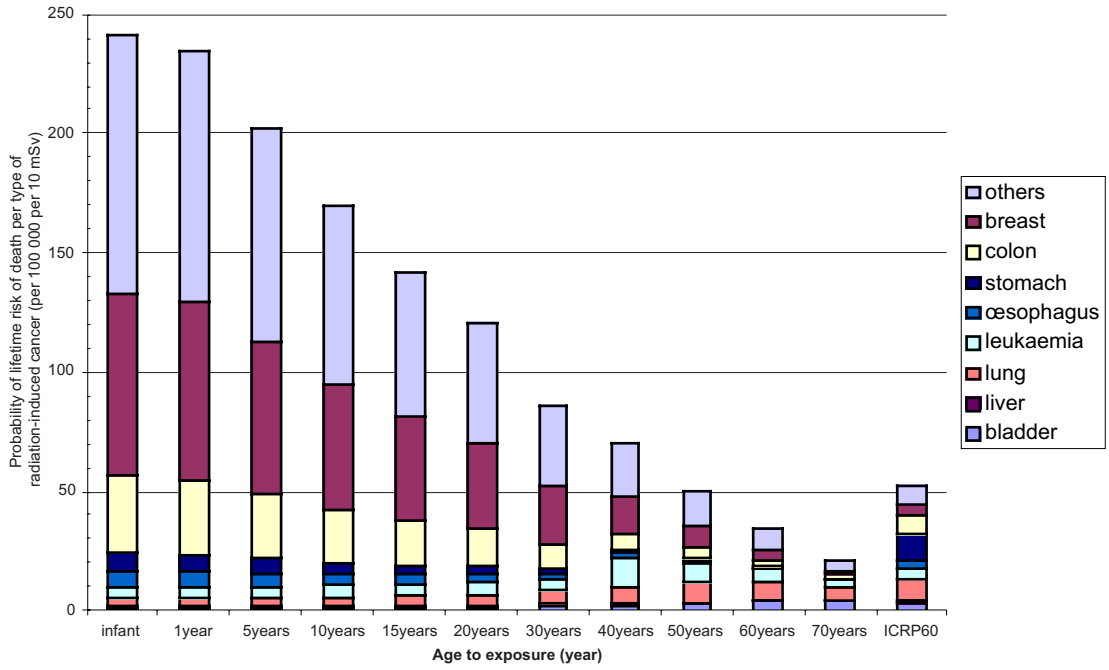


Figure 4. **Cumulative bar charts of lifetime risks of death per age to exposure to and per type of radiation-induced cancer (UNSCEAR 2000 model). *For women***

By way of comparison, the values adopted in ICRP Publication 60 are shown; demographic data, France 1994; "equivalent dose to each organ" equal to 10 mSv and use of a DDREF of 2.

Analysis of Figures 3 and 4 shows that certain organs have considerable impact: the breast in women and to a lesser extent the liver in men.

It can be seen that age at the time of exposure also has an effect since the same dose results in a risk that is seven times lower in a man of 70 than in a male infant and ten times lower in a woman of 70 than in a female infant. To illustrate this aspect, Table 2 gives the health effect modification factors to be applied to the dose-risk relationship as a function of age. These factors are taken from a 1995 ICRP proposal that was never published.

Table 2. Health effect modification factors as a function of the age of the individual exposed (average for males and females combined)

Age (years)	Health effect correction factor
1	3
5	2.5
10	2
15	1.5
adult	*1*
50	0.5
70	0.3

It follows that the nominal risk coefficients proposed by the ICRP for adults should be used with caution.

2. TOOLS FOR DETERMINING THE RISK OF OCCURRENCE OF STOCHASTIC EFFECTS

2.1. Applying the ICRP model to simple exposure cases in the absence of detailed information

The aim of this section is to propose a simple tool for determining the severity levels that will be used to classify events involving exposure to ionising radiation.

To this end, and on the basis of the ICRP dose-effect relationships (see Section I.2.2 above), the following four figures will be used to give a rough estimate of the lifetime probability of developing fatal cancer corresponding to the whole body dose (effective dose) received by the individual exposed.

The first two figures (5.1 and 5.2) relate to occupational exposure. The other two (6.1 and 6.2) relate to exposure of members of the public. In both cases, the first figure indicates the situation for individuals who have received doses of at least 50 mSv, and the second gives a more detailed picture for lower doses.

Thus, whenever the whole body effective dose is known, it is simply a question of using:

- **the pink curve** for low doses (< 0.2 Sv) **AND** low dose rates (< 0.1 Gy/h)

or

- **the blue curve** for high doses (> 0.2 Sv) **OR** high dose rates (> 0.1 Gy/h).

Two examples of how to use the curves are given on Page A1.14.

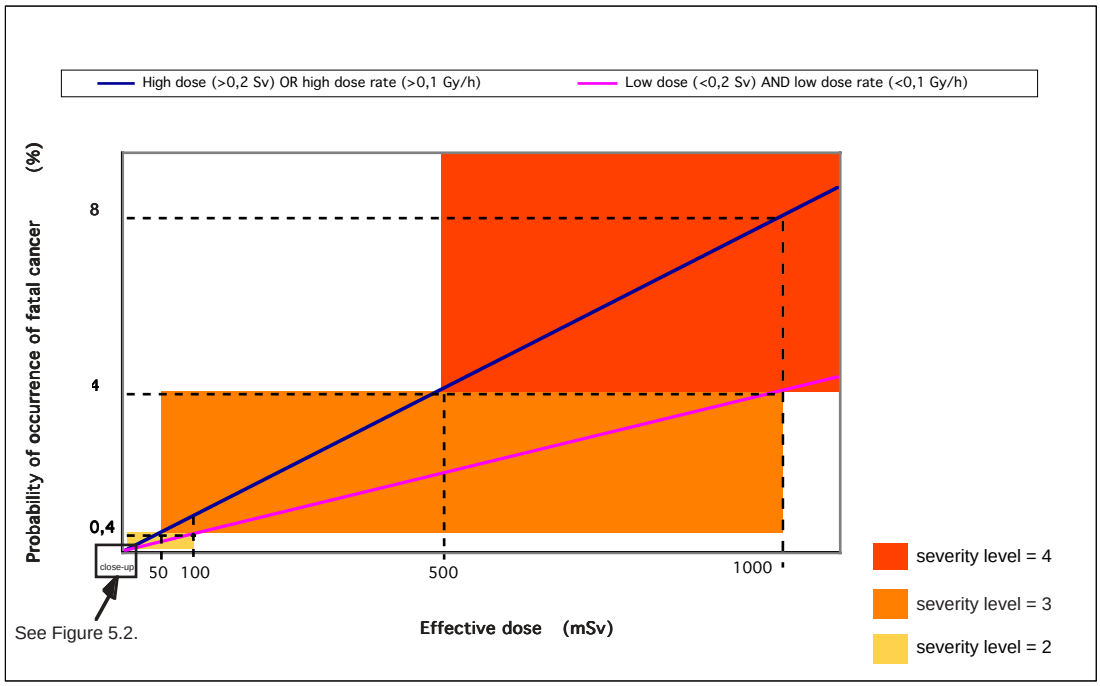


Figure 5.1 **Probability of fatal cancer occurring as a function of dose and dose rate for an exposed worker as per model in ICRP Publication 60 and correspondence with severity levels on scale**

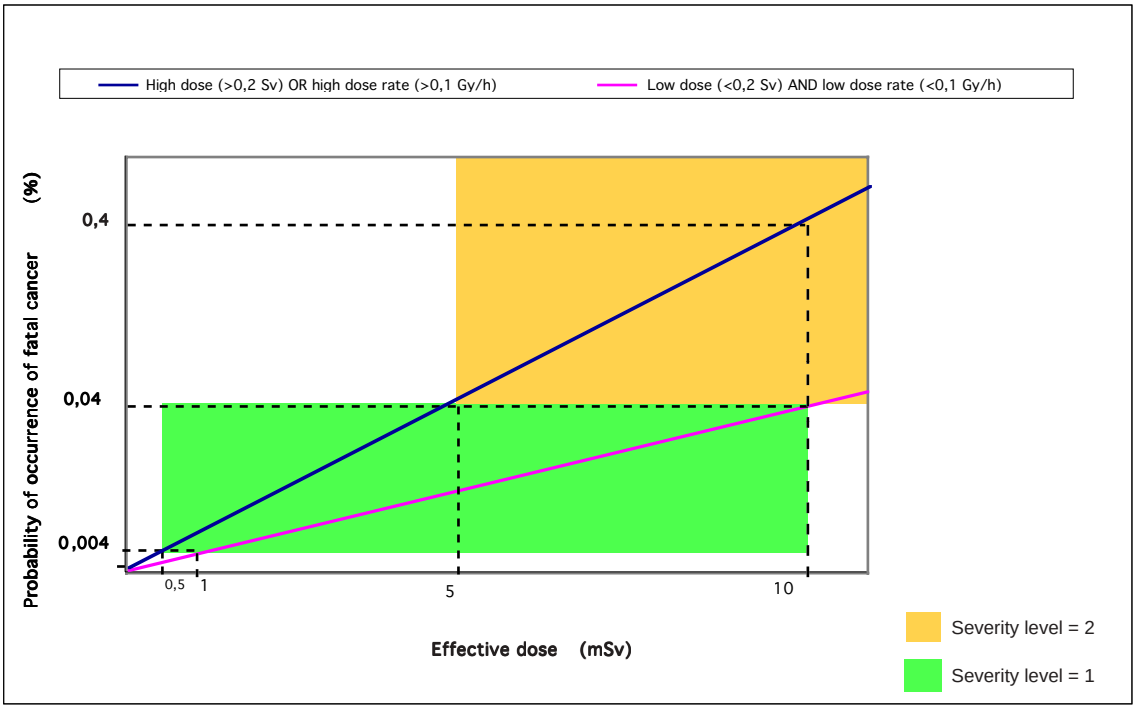


Figure 5.2 **Probability of fatal cancer occurring as a function of dose and dose rate for an exposed worker as per model in ICRP Publication 60 and correspondence with severity levels on scale. Doses of less than 10 mSv**

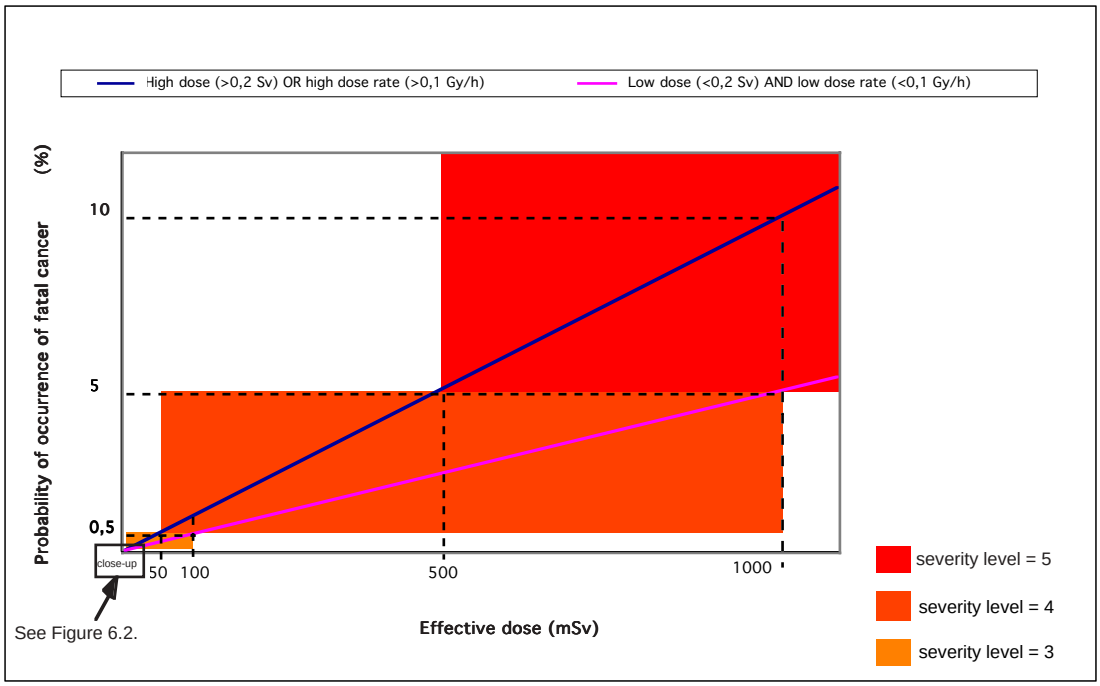


Figure 6.1 **Probability of fatal cancer occurring as a function of dose and dose rate for an exposed member of the public as per model in ICRP Publication 60 and correspondence with severity levels on scale**

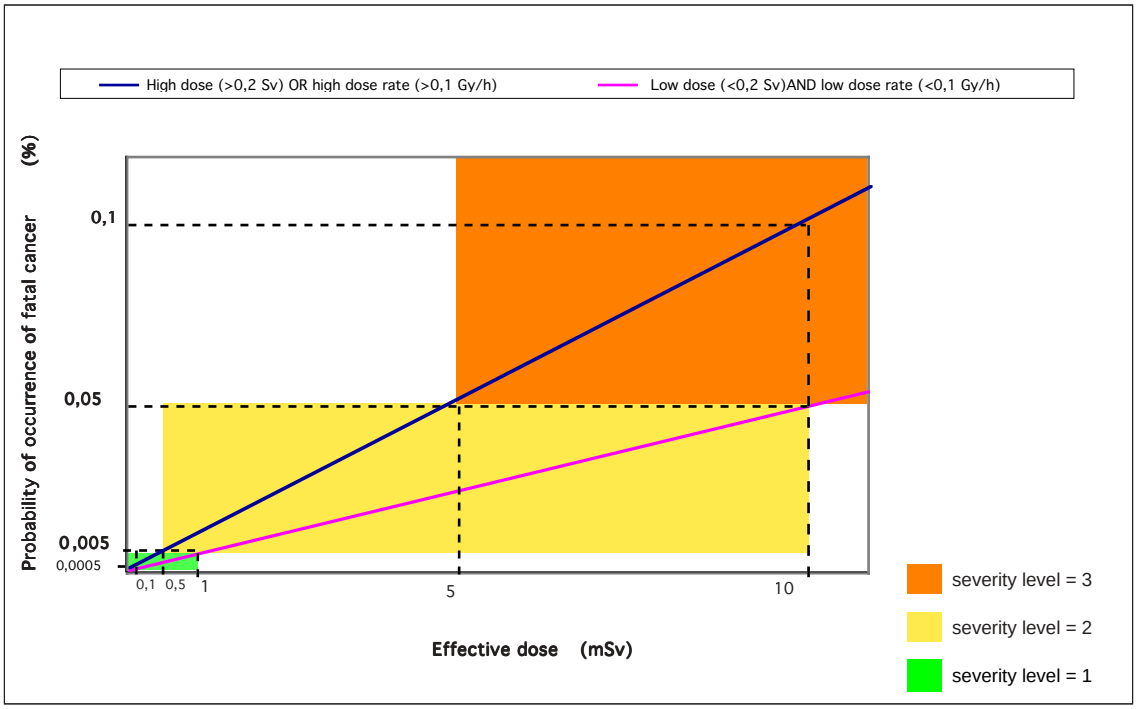


Figure 6.2 **Probability of fatal cancer occurring as a function of dose and dose rate for an exposed member of the public as per model in ICRP Publication 60 and correspondence with severity levels on scale. Doses of less than 10 mSv**

Examples of use:

1. A worker receives a whole body dose of 600 mSv within a few minutes.

The event has to be situated on the blue curve in Figure 5.1 (exposure took place at a high dose rate of more than 100 mGy/h and the dose received was greater than 200 mSv): the corresponding risk factor is 4.

2. In an incident situation, a member of the public receives a whole body dose estimated at 2 mSv over several days.

Since the dose rate is far below 100 mGy/h and the dose received less than 200 mSv, the event should be situated on the pink curve in Figure 6.2: the corresponding risk factor is 2.

2.2. Using ASQRAD® to specify individual risk as a function of age, gender, irradiated organ, dose and dose rate

There are more complex tools for calculating individual risk associated with exposure. In some special cases, there may be no alternative but to use them (exposure of the public including a variety of age ranges for example). In the sections that follow, the ASQRAD® (Assessment System for Quantification of Radiological Detriment) application is described.

2.2.1. Description of the ASQRAD® application

The ASQRAD® application was developed jointly by the CEPN and the NRPB with the aim of providing a generic structure for the study of radiological detriment measurements[8]. One of its uses is to quantify the detriment associated with stochastic somatic effects in the cases of doses to individuals. It comprises a database containing demographic data for various countries and a selection of mathematical models for calculating the lifetime risk of radiation-induced cancer established by various national and international radiological protection bodies. The particularity of this application is that it has been designed to be flexible, giving the user the opportunity to modify the parameters of the models.

8 Degrange *et al*., 1997.

2.2.2. Calculating the lifetime risk of exposure-induced death associated with exposure of an individual to radiation with a low linear energy transfer rate delivered at low doses and low dose rates

As shown in Figure 7, calculating risk using the ASQRAD application involves entering the following parameters on a screen or selecting them (if default parameters are given):

1) parameters characterising the type of exposure (uniform to the whole body or to certain organs), the individual (age at time of exposure and gender) and the average dose distribution to the organs covered by the risk model (or the whole body dose if this type of exposure is involved),

2) a lifetime risk model, i.e. association of specific dose-risk models for different types of cancer with the calculation hypotheses concerning the methods used to project the risk to the entire lifetime and transfer it between populations,

3) data characterising the demographic origin of the exposed population, i.e. the basic mortality rate for each type of cancer covered by the lifetime risk model and the general mortality rates that are given by gender and age range (the application includes data libraries),

4) hypotheses relating to latency periods and plateau (length of time during which the risk is present) for each cancer area covered by the lifetime risk model selected, and

5) the dose and dose rate effectiveness factor (DDREF).

2.2.3. Definition of lifetime risk indicators

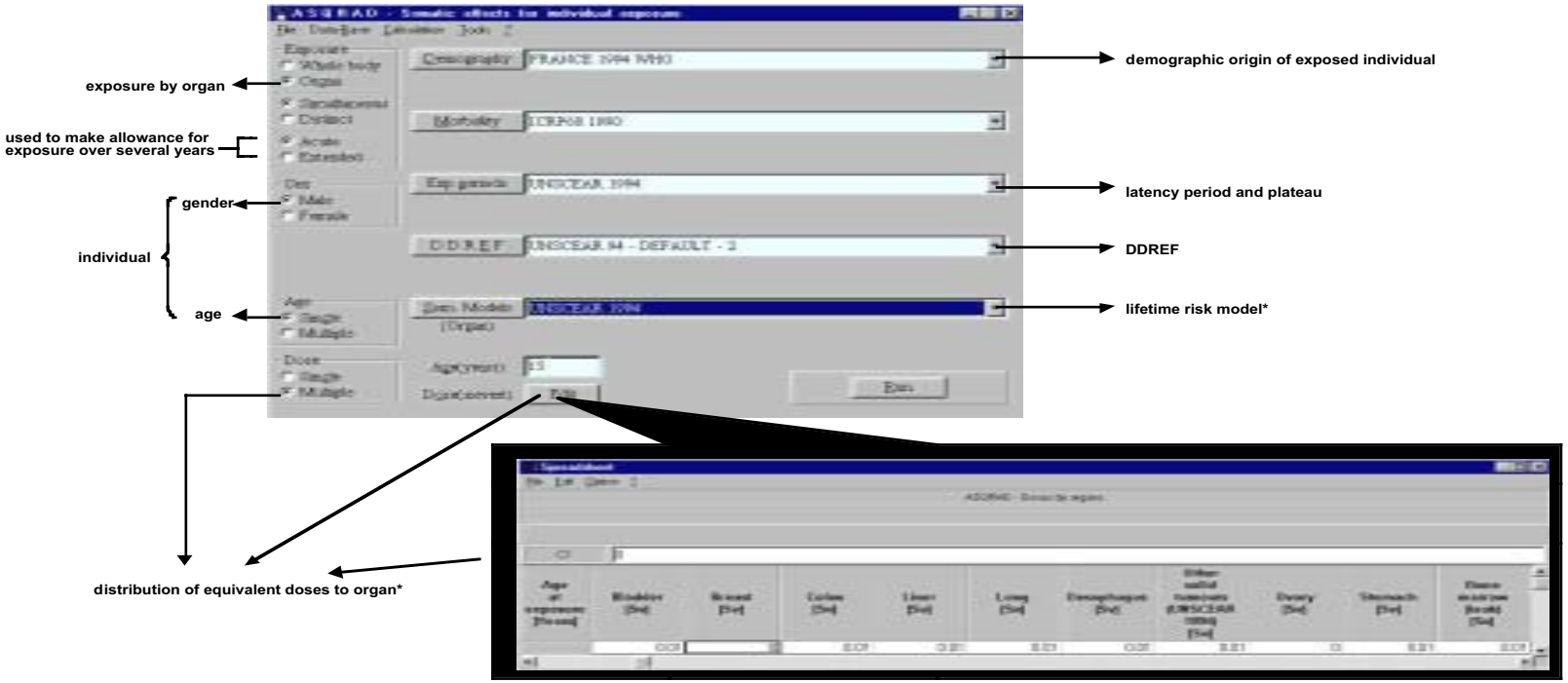
The definition of lifetime risk has been the focus of much attention since the late eighties[9] Inasmuch as risk models adjusted to epidemiological data and the corresponding risk coefficients are available, it seems worth having indicators that sum up lifetime detriment due to exposure to ionising radiation. Two quantities[10] have been used by numerous bodies: quantities expressing the lifetime excess risk of death and quantities expressing the reduction in life expectancy. Calculations of the lifetime risk of exposure-induced

9 Pierce *et al*., 1989.

10 Thomas *et al*., 1992.

death carried out with ASQRAD®, which are based on demographic analysis methods[11], can be used to assess these two types of lifetime risk indicators. Only the first will be described here since it is the risk indicator adopted for establishing severity levels on the scale.

11 Pressat, 1983



*Organs at risk for which the equivalent dose to the organ has to be determined correspond to types of cancer for which specific dose-risk models have been created.

Figure 7. Screenshot of ASQRAD® application window for entering parameters of model used to calculate risk of exposure-induced death in the case of an exposure scenario for an individual

2.2.4. Lifetime risk of exposure-induced death

The expression "risk of exposure-induced death" can be abbreviated to **REID**. This quantity corresponds to the lifetime risk for an individual of gender "s" and demographic origin "country" of dying of cancer resulting from exposure at age "a_0". Given that several organs "c" are exposed simultaneously, each at average doses to the organ "D_c", the total whole body risk, $REID_{total}$, is given by the sum of the specific risks per type of cancer, $REID_c$, i.e. by the following relationship:

$$REID_{total} = \sum_{c} REID_c$$

The specific risk per type of cancer is equal to the sum accumulated over the entire lifetime of the exposed individual of the excess risk of death from cancer (i.e. the difference in mortality rates, with and without exposure) determined by his survival at the age in question. The mathematical expression of the specific lifetime risk per type of cancer can therefore be written as follows:

$$REID_{s,c}^{mod,country}(a_0, D_c) = \int_{a_0}^{\infty} \Delta m_{s,c}^{mod,country}(a|a_0, D_C) \times S_s^{*\,mod,country}(a|a_0, D_c)\, da$$

(as the number of cases per 100,000)

where:

$\Delta m_{s,c}^{mod,country}(a|a_0, D_C) = m_{s,c}^{country}(a) \times \Delta RR_{s,c}^{mod}(a, a_0, D_c)$ if the risk model is a relative one

$$S_s^{*\,mod,country}(a|a_0, D_c) = \frac{S_s^{*\,mod,country}(a, a_0, D_c)}{S_s^{country}(a_0)}$$

$$S_s^{*\,mod,country}(a, a_0, D_c) = \exp\left\{-\int_0^a m_s^{*\,mod,country}(u, a_0, D_c)\, du\right\}$$

$$S_s^{country}(a_0) = \exp\left\{-\int_0^a m_s^{country}(u)\, du\right\}$$

$$m_s^{*\,mod,country}(u, a_0, D_c) = m_s^{country}(u) + \Delta m_{s,c}^{mod,country}(u|a_0, D_c)$$

in which the following notations have been adopted:

mod: is the dose-risk model used by the radiological protection body in question,

country: is the demographic origin of the exposed individual (census year for basic mortality rates),

c: is the type of cancer and corresponding organ/tissue,

s: is the gender of the exposed individual,

*****: means "modified by exposure to ionising radiation",

and in which the following notations have been adopted for variables:

$\mathbf{a_0}$: age at time of exposure,

$\mathbf{D_c}$: equivalent dose to organ **a**: age reached,

u: age,

and where

- $REID_{s,c}^{mod,country}(a_0,D_c)$ is the lifetime risk of exposure-induced death corresponding to risk model "mod" in question and specific to the type of cancer "c" considered, for an exposed individual of gender "s" and demographic origin "country"; since there parameters are fixed, REID depends on age at the time of exposure "a_0" and the equivalent doe to the organ "D_c",
- $\Delta m_{s,c}^{mod,country}(a|a_{0,}D_c)$ is the excess exposure-induced mortality, given that the individual was exposed at age "a_0", corresponding to risk model "mod" in question and which is specific to the type of cancer "c" being considered, for an individual of gender "s" and demographic origin "country"; in the case of multiplicative (or additive) dose-excess risk models, the relative excess risk $\Delta RR_{s,c}^{mod}(a,a_0,D_c)$ (or the absolute excess risk $\Delta AR_{s,c}^{mod}(a,a_0,D_c)$ may depend on age reached "a" or the age at the time of exposure "a_0" and depends on the equivalent dose to the organ "D_c" for gender "s" and type of cancer "c" considered,
- $m_{s,c}^{country}(a)$ is the basic rate of mortality[12] for the "country", gender "s" and type of cancer "c" considered; since these parameters are fixed, the rate of mortality depends on age and is established for one census year or a group of census years,
- $S_s^{*mod,country}(a|a_{0,}D_c)$ is the conditional probability of survival at the age reached "a",

given that the individual is alive at age "a_0", modified by exposure of the individual from the "country" in question, of gender "s" and who was exposed at age "a_0" to the equivalent dose to the organ "D_c",

12 The specific rate of mortality for each type of cancer is the probability per unit of time that an individual of a given age, gender and demographic origin will die from the type of cancer being considered.

- $S_s^{*mod,country}(a,a_0,D_c)$ is the probability of survival at the age reached "a", modified by exposure of the individual from the "country" in question, of gender "s" and who was exposed at age "a_0" to the equivalent dose to the organ "D_c",
- $S_s^{country}(a_0)$ is the probability of survival at the age at the time of exposure "a_0" for an individual from the "country" in question of gender "s",
- $m_s^{*mod,country}(u,a_0D_c)$ is the general rate of mortality at age "u", modified by exposure of the individual from the "country" in question, of gender "s" and who was exposed at age "a_0" to the equivalent dose to the organ "D_c",
- $m_s^{country}(u)$ is the general basic rate of mortality at age "u" of an individual from the "country" considered of gender "s".

The REID indicator does not give any information about age at the time of death. It simply represents the risk of dying from cancer caused by a particular type of exposure as opposed to the risk of dying from any other cause. This is why more detailed information is given by the curve showing the variation in the risk of exposure-induced mortality as a function of age "a" reached, which is given by $\Delta m_{s,c}^{mod,country}(a|a_0,D_C)\times S_s^{*mod,country}(a|a_0,D_c)$**:** this is the **"age at death probability density"**, normalised so that the surface area circumscribed by the curve is equal to the lifetime risk of exposure-induced death, REID.

Tables 3a, 3b and 3c below show all the characteristics available for lifetime risk models developed by international radiological protection bodies such as the ICRP [ICRP, 1991] and UNSCEAR [UNSCEAR, 1994][13] and by national bodies such as BEIR [BEIR V, 1990][14] and the NRPB [NRPB, 1993][15].

13 The UNSCEAR 1994 model is available in the ASQRAD® software

14 The BEIR V mosel is available in the ASQRAD® software

15 The NRPB 1993 model is available in the ASQRAD® software

Table 3(a) Specifications of mathematical models used to calculate specific lifetime risks per type of cancer, developed by BEIR [BEIR V, 1990]

Cancer area or "group" of cancers (code No. 8 in international classification of causes of death [ICD, 1967]	**Basic epidemiological data** (i) Cohort of Japanese survivors of Hiroshima and Nagasaki (denoted as LSS) or medical data (ii) Incidence data, **I,** or mortality data, **M** (iii) Bibliographical reference	**Dependency of relative excess risk, ΔR R** (i) age at time of exposure, $\mathbf{a_0}$ (ii) gender, **s** (iii) time elapsed since exposure, **t** (iv) weighted dose, **D** (in Sv)	**Shape of dose-response relationship** Linear, **L** or linear quadratic **LQ**	**Latency and plateau**	**Method used to project risk to lifetime** Multiplicative ⊗ or Additive ⊕	**Method used to transfer risk between populations** Multiplicative ⊗ or Additive ⊕	**DDREF**
Leukaemia (ICD 204-207)	LSS 1956-85 / M [Shimizu *et al*., 1987]	$\Delta RR_{a0,t}(D)$	LQ	2 and 27 years	None	⊗	None
Breast cancer (women) (ICD 174)	• LSS 1950-85 / M [Shimizu *et al*., 1987] • Canadian Fluoroscopy Study 1950-80 / M [Miller *et al*., 1989] • 3 incidence studies [cf. Table 4^E-1 p.208: BEIR V, 1990]	$\Delta RR(D,a_0,t)$	L	10 and 100 years	None	⊗	None
Cancers of the digestive system (ICD 150-159)	LSS 1956-85 / M [Shimizu *et al*., 1987]	$\Delta RR_s(D,a_0)$	L	10 and 100 years	⊗ constant	⊗	None
Cancers of the respiratory system (ICD 160-163)	LSS 1956-85 / M [Shimizu *et al*., 1987]	$\Delta RR_s(D,t)$	L	10 and 100 years	None	⊕ preferable	None
Other types of cancer (ICD 140-209 other than those listed above)	LSS 1956-85 / M [Shimizu *et al*., 1987]	$\Delta RR(D,a_0)$	L	10 and 100 years	⊗ constant	⊗	None

Table 3(b) Specifications of mathematical models used to calculate specific lifetime risks per type of cancer, contained in ICRP Publication 60 [ICRP, 1991], [ICRP, 1991(a)]

Cancer area or "group" of cancers	**Basic epidemiological data** (i) Cohort of Japanese survivors of Hiroshima and Nagasaki (denoted as LSS) or medical data (ii) Incidence data, **I** or mortality data, **M** (iii) Bibliographical reference	**Dependency of relative excess risk, ΔRR or absolute excess risk, ΔAR (in 10^{-4} PY Sv)$^{-1}$** (i) age at time of exposure, $\mathbf{a_0}$ (ii) gender, **s** (iii) time elapsed since exposure, **t** (iv) weighted dose, **D** (in Sv)	**Shape of dose-response relationship** Linear, **L** or linear quadratic **LQ**	**Latency and plateau**	**Method used to project risk to lifetime** Multiplicative⊗ or Additive ⊕	**Method used to transfer risk between populations** Multiplicativ⊗ or Additive ⊕	**DDREF**
Leukaemia	LSS 1950-85 / M [Shimizu *et al*., 1988]	$\Delta RR_{s,a0}(D)$ and $\Delta AR_{s,a0}(D)$	L	2 and 40 years	⊗ constant	⊗ and ⊕ (NIH)	2
Oesophagus	LSS 1956-85 / M [Shimizu *et al*., 1988]	$\Delta RR_{s}(D)$ and $\Delta AR_{s,a0}(D)$	L	10 and 100 years	⊗ constant	⊗ and ⊕ (NIH)	2
Stomach	LSS 1956-85 / M [Shimizu *et al*., 1988]	$\Delta RR_{s,a0}(D)$ and $\Delta AR_{s,a0}(D)$	L	10 and 100 years	⊗ constant	⊗ and ⊕ (NIH)	2
Colon	LSS 1956-85 / M [Shimizu *et al*., 1988]	$\Delta RR_{s,a0}(D)$ and $\Delta AR_{s,a0}(D)$	L	10 and 100 years	⊗ constant	⊗ and ⊕ (NIH)	2
Lung	LSS 1956-85 / M [Shimizu *et al*., 1988]	$\Delta RR_{s,a0}(D)$ and $\Delta AR_{s,a0}(D)$	L	10 and 100 years	⊗ constant	⊗ and ⊕ (NIH)	2
Bladder	LSS 1956-85 / M [Shimizu *et al*., 1988]	$\Delta RR(D)$ and $\Delta AR_{s,a0}(D)$	L	10 and 100 years	⊗ constant	⊗ and ⊕ (NIH)	2
Breast (women)	LSS 1956-85 / M [Shimizu *et al*., 1988]	$\Delta RR_{s,a0}(D)$ and $\Delta AR_{s,a0}(D)$	L	10 and 100 years	⊗ constant	⊗ and ⊕ (NIH)	2
Ovary	LSS 1956-85 / M [Shimizu *et al*., 1988]	$\Delta RR_{s}(D)$ and $\Delta AR_{s,a0}(D)$	L	10 and 100 years	⊗ constant	⊗ and ⊕ (NIH)	2
Liver	M estimated (high LET) [BEIR V, 1990]	[1.] Lifetime risk of fatal cancer at low LET rate and low dose = constant = 0.15×10^{-2} Sv^{-1}					
Thyroid	M [NCRP, 1985]	Lifetime risk of fatal cancer at low LET rate and low dose = constant = 0.075×10^{-2} Sv^{-1}					
Bone surface	M estimated (I and high LET) [BEIR IV, 1988]	Lifetime risk of fatal cancer at low LET rate and low dose = constant = 0.047×10^{-2} Sv^{-1}					
Skin	M estimated (I) [ICRP, 1991]	Lifetime risk of fatal cancer at low LET rate and low dose = constant = 0.02×10^{-2} Sv^{-1}					

Table 3(c) Specifications of models used to calculate specific lifetime risks per type of cancer, developed by NRPB [NRPB, 1993]

Cancer area or "group" of cancers	**Basic epidemiological data** (i) Cohort of Japanese survivors (LSS) or medical data (ii) Incidence data, **I**, or mortality data, **M** (iii) Bibliographical reference	**Dependency of relative excess risk, ΔR R or absolute excess risk, ΔAR (in 10^{-4} PY Sv)$^{-1}$**(i) age at time of exposure, $\mathbf{a_0}$ (ii) gender, **s** (iii) time elapsed since exposure, **t** (iv) weighted dose, **D** (in Sv)	**Shape of dose-response relationship** Linear, **L** or linear quadratic **LQ**	**Latency and plateau**	**Method used to project risk to lifetime** Multiplicative ⊗ or Additive ⊕	**Method used to transfer risk between populations** Multiplicative ⊗ or Additive ⊕	**DDREF**
Leukaemia (with the exception of chronic lymphatic leukaemia)	LSS 1956-85 / M [Shimizu *et al*., 1987]	$\Delta RR_{a0,t}(D)$	LQ	2 and 40 years	None	⊗	None
Breast (women)	• Massachusetts Fluoroscopy Study / M [Hrubec *et al*., 1989] • N.Y. Postpartum Mastitis Study / I [Shore *et al*., 1986]	$\Delta RR(D,a_0)$ [Stather *et al*., 1988] [Gilbert, 1985]	L	10 and 100 years	⊗ constant	⊗	2
Lung	LSS 1956-85 / M [Shimizu *et al*., 1987]	$\Delta RR_s(D,t)$	L	10 and 100 years	None	⊗	2
Thyroid	Rochester Thymus Study / I [Shore *et al*., 1985]	$\Delta AR(D,a_0)$ [NCRP, 1985]	L	5 and 100 years	⊕ constant	⊗	2
Bone	German patients with intakes of ^{224}Ra / M [BEIR IV, 1988]	ΔAR(D)	L	2 and 40 years	⊕ constant	⊗	1
Liver	European patients given Thorotrast [BEIR IV, 1988]	ΔAR(D)	L	20 and 100 years	⊕ constant	⊗	2
Colon	LSS 1956-85 / M [Shimizu *et al*., 1987]	$\Delta RR_s(D,a_0)$	L	10 and 100 years	⊗ constant	⊗	2

Table 3(c) contd. Specifications of models used to calculate specific lifetime risks per type of cancer, developed by NRPB [NRPB, 1993]

Cancer area or "group" of cancers	**Basic epidemiological data** (i) Cohort of Japanese survivors (LSS) or medical data (ii) Incidence data, **I**, or mortality data, **M** (iii) Bibliographical reference	**Dependency of relative excess risk, ΔR R or absolute excess risk, ΔAR (in 10^{-4} PY Sv)$^{-1}$** (i) age at time of exposure, $\mathbf{a_0}$ (ii) gender, **s** (iii) time elapsed since exposure, **t** (iv) weighted dose, **D** (in Sv)	**Shape of dose-response relationship** Linear, **L** or linear quadratic **LQ**	**Latency and plateau**	**Method used to project risk to lifetime** Multiplicative ⊗ or Additive ⊕	**Method used to transfer risk between populations** Multiplicative ⊗ or Additive ⊕	**DDREF**
Stomach	LSS 1956-85 / M [Shimizu *et al*., 1987]	$\Delta RR_s(D,a_0)$	L	10 and 100 years	⊗ constant	⊗	2
Skin	North American children irradiated for ringworm of the scalp / I: [BEIR III, 1980] and [Shore *et al*., 1984]	ΔAR(D)	L	10 and 100 years	⊕ constant	⊗	2
Remainder	LSS 1956-85 / M [Shimizu *et al*., 1987]	$\Delta RR(D,a_0)$	L	10 and 100 years	⊗ constant	⊗	2

Table 3(d) Specifications of mathematical models used to calculate specific lifetime risks per type of cancer, developed by UNSCEAR in 1994 [UNSCEAR, 1994]

Cancer area or "group" of cancers	**Basic epidemiological data** (i) Cohort of Japanese survivors of Hiroshima and Nagasaki (denoted as LSS) (ii) Incidence data, **I**, or mortality data **M** (iii) Bibliographical reference	**Dependency of relative excess risk, ΔRR or absolute excess risk, ΔAR (in 10^{-4} PY Sv)$^{-1}$** (i) age at time of exposure, $\mathbf{a_0}$ (ii) gender, **s** (iii) time elapsed since exposure, **t** (iv) weighted dose, **D** (in Sv)	**Shape of dose-response relationship** Linear, **L** or linear quadratic **LQ**	**Latency and plateau**	**Method used to project risk to lifetime**	**DDREF**
Leukaemia	LSS 1950-87 / I [Preston *et al.*, 1994]	$\Delta AR_s(D,t)$	LQ	2 and 100 years	None	None
Oesophagus	LSS 1950-87 / M [Ron *et al.*, 1994]	$\Delta RR_s(D,a_0)$	L	10 and 100 years	3 methods shown in Figure A8.3	2 suggestions
Stomach	LSS 1950-87 / M [Ron *et al.*, 1994]	$\Delta RR_s(D,a_0)$	L	10 and 100 years	3 methods shown in Figure A8.3	2 suggestions
Colon	LSS 1950-87 / M [Ron *et al.*, 1994]	$\Delta RR_s(D,a_0)$	L	10 and 100 years	3 methods shown in Figure A8.3	2 suggestions
Liver	LSS 1950-87 / M [Ron *et al.*, 1994]	$\Delta RR_s(D,a_0)$	L	10 and 100 years	3 methods shown in Figure A8.3	2 suggestions
Lung	LSS 1950-87 / M [Ron *et al.*, 1994]	$\Delta RR_s(D,a_0)$	L	10 and 100 years	3 methods shown in Figure A8.3	2 suggestions
Bladder	LSS 1950-87 / M [Ron *et al.*, 1994]	$\Delta RR_s(D,a_0)$	L	10 and 100 years	3 methods shown in Figure A8.3	2 suggestions
Breast (women)	LSS 1950-87 / M [Ron *et al.*, 1994]	$\Delta RR_s(D,a_0)$	L	10 and 100 years	3 methods shown in Figure A8.3	2 suggestions
Ovary	LSS 1950-87 / M [Ron *et al.*, 1994]	$\Delta RR_s(D,a_0)$	L	10 and 100 years	3 methods shown in Figure A8.3	2 suggestions
Other solid tumours	LSS 1950-87 / M [Ron *et al.*, 1994]	$\Delta RR_s(D,a_0)$	L	10 and 100 years	3 methods shown in Figure A8.3	2 suggestions

BIBLIOGRAPHICAL REFERENCES

[Arlie Conference, 1999] « Bridging Radiation Policy and Science ». Conclusions of Arlie Conference. Warrenton, Virginie, USA, 1-5 December 1999.

[BEIR V, 1990] Committee on the Biological Effects of Ionizing Radiations (BEIR V). Health Effects of Exposure to Low Levels of Ionizing Radiation. United States National Academy of Sciences, National Research Council. National Academy Press, Washington. 1990.

[BEIR IV, 1988] Committee on the Biological Effects of Ionizing Radiations (BEIR IV). Health Risks of Radon and Other Internally Deposited Alpha-Emitters. United States National Academy of Sciences, National Research Council. National Academy Press, Washington. 1988.

[Degrange *et al.*, 1997] Degrange J.P., Schneider T., Muirhead C., Haylock R. ASQRAD : un logiciel pour l'évaluation du risque radiologique, Produit nouveau. Radioprotection. 32(2):237-244.1997.

[Hrubec *et al.*, 1989] Hrubec Z., Boice J., Monson R. and Rosenstein M. Breast Cancer after Multiple Chest Fluoroscopies: Second follow-up of Massachusetts Women with Tuberculosis. Cancer Res. 49:229-234. 1989.

[ICD, 1967] Eighth Revision International Classification of Diseases. Vol. 1. Public Health Service Publication No. 1639, Washington, D.C. Government Printing Office. 1967.

[ICRP, 1991] ICRP, Recommendations of the International Commission on Radiological Protection, 1990, ICRP Publication 60. Pergamon Press, Oxford, UK. 1991.

[Miller *et al.*, 1989] Miller A.B., Howe G.R., Sherman G.J., Lindsay J.P., Yaffe M.J., Dinner P.J., Risch H.A. and Preston D.L. Mortality from Breast Cancer after Irradiation during Fluoroscopic Examination in Patients being treated for Tuberculosis. N Engl J Med. 9; 321(19):1285-9. 1989.

[NCRP, 1985] National Council on Radiation Protection and Measurements. Induction of Thyroid Cancer by Ionising Radiation. NCRP Report No. 80. NCRP, Bethesda, MD, USA. 1985.

[NRPB, 1993(a)] National Radiological Protection Board. Occupational, Public and Medical Exposure. Documents of the NRPB, Chilton, UK. 4(2). 1993.

[Pierce *et al.*, 1989] Pierce D.A. and Vaeth M. Cancer Risk Estimation from the A-Bomb Survivors: Extrapolation to Low Doses, Use of Relative Risk Models and other Uncertainties. In Low Dose Radiation: Biological Bases of Risk Assessment (Eds K.F. Baverstock and J.W. Stather). London, Taylor and Francis. 1989.

[Pierce, Preston, 2000] Radiation-Related Cancer Risks at Low Doses among Atomic Bomb Survivors. Radiation Research, Volume 154, N°2, pp.178-186, 2000.

[Pressat, 1983] Pressat R. L'analyse démographique. Concepts – Méthodes – Résultats. Presses Universitaires de France, Paris, 1983.

[Preston *et al.*, 1994] Preston D.L., Kusumi S., Tomonaga M. et al. Cancer Incidence in

Atomic Bomb Survivors. Part III: Leukaemia, Lymphoma and multiple Myeloma, 1950-87. RERF TR/24-92. 1992. and Radiat Res. 137:S68-S97. 1994.

[Ron *et al*., 1994] Ron E., Preston D.L., Mabuchi K. et al. Cancer Incidence in Atomic Bomb Survivors. Part IV: Comparison of Cancer Incidence and Mortality. Radiat. Res. 137:S98-S112. 1994.

[Shimizu *et al*., 1987] Shimizu Y., Kato H., Schull W.J., Preston D.L., Fujita S. and Pierce D.A. Life Span Study Report 11, Part 1. Comparison of Risk Coefficients for Site-Specific Cancer Mortality Based on the DS86 and T65DR Shielded Kerma and Organ Doses. Technical Report RERF TR 12-87. Hiroshima Radiation Effects Research Foundation. 1987.

[Shimizu *et al*., 1988] Shimizu Y., Kato H. and Schull W.J. Life Span Study Report 11, Part 2. Cancer Mortality in the Years 1950-85 Based on the Recently Revised Doses (DS86). Technical Report RERF TR 5-88. Hiroshima Radiation Effects Research Foundation. 1988.

[Shore *et al*., 1984] Shore R.E., Albert R.E., Reed M., Harley N. and Pasternack B.S. Skin Cancer Incidence among Children irradiated for Ringworm of the Scalp. Radiat. Res. 100:192-204. 1984.

[Shore *et al*., 1985] Shore R.E., Woodard E., Hildreth N., Dvoretsky P., Hempelmann L. and Pasternack B. Thyroid tumours following thymus irradiation. J. Natl. Cancer Inst. 74:1177-1184. 1985.

[Shore *et al*., 1986] Shore R.E., Hildreth N., Woodward E., Dvoretsky P., Hempelmann L. and Pasternack B. Breast Cancer among Women given X-ray Therapy for Acute Postpartum Mastitis. J. Natl. Cancer Inst. 77:689-696. 1986.

[Thomas *et al*., 1992] Thomas D., Darby S., Fagnani F., Hubert P., Vaeth M. and Weiss K. Definition and Estimation of Lifetime Detriment from Radiation Exposures: Principles and Methods. Health Phys. 63(3):259-272. 1992.

[UNSCEAR, 1994] United Nations. Sources and Effects of Ionizing Radiation. United Nations Scientific Committee on the Effects of Atomic Radiation, United Nations, New York. 1994.

[UNSCEAR, 2000(a)] United Nations. Sources and Effects of Ionizing Radiation. United Nations Scientific Committee on the Effects of Atomic Radiation, Volume I: Sources. United Nations, New York. 2000.

[UNSCEAR, 2000(b)] United Nations. Sources and Effects of Ionizing Radiation. United Nations Scientific Committee on the Effects of Atomic Radiation, Volume II: Effects. United Nations, New York. 2000.

[Wingspread Conference, 1997] "Creating a Strategy for Science-Based National Strategy: Addressing Conflicting Views on the Health Risks of Low Level Ionizing Radiation". Conclusions of the Wingspread Conference, Wisconsin, USA, July-August 1997.

REPORT N° 276

PROPOSED CLASSIFICATION SCALE FOR RADIOLOGICAL INCIDENTS AND ACCIDENTS

APPENDIX 2

Method and tools available for calculating the risk of occurrence of deterministic effects as a function of dose and dose rate (1996 NRPB model)

Pascal CROÜAIL, David COLLIN, Christian LEFAURE

CONTENTS

LIST OF TABLES AND FIGURES

Appendix 2

Method and tools available for calculating the risk of occurrence of deterministic effects as a function of dose and dose rate (1996 NRPB model[1])

DETERMINISTIC: "determined in a causal manner by previous events"

1. RISK CALCULATION METHOD

1.1. Origin, nature and classification of deterministic effects

When ionising radiation reacts with the body, energy is deposited in a random manner. However, **at a certain dose level**, there may be a high cellular lethality rate, which could lead to changes in tissues that can be detected **in the short term** (between a few hours and one month after irradiation).

The way in which tissues react to radiation, be it general or partial, depends on the survival rate of the cells of which they are comprised and therefore on their sensitivity to radiation. The destruction of a large number of cells, which cannot be offset by proliferation of the surviving ones, may result in severe anatomical and/or functional modifications that can be detected by clinical examination. The pathological effect detected is known as the deterministic effect.

Two types of deterministic effects are described in the literature:

- Non-lethal effects, i.e. those which are not life-threatening for the individual exposed,
- Lethal effects, i.e. those which could result in the death of the individual exposed.

In this report, a further distinction is made to sub-divide non-lethal effects into two sub-groups, depending on whether they are disabling or not.

[1] NRPB. Risk from Deterministic Effects of Ionising Radiation, Document of the NRPB Volume 7 No. 3, 1996.

Non-lethal disabling effects are those which are difficult or even impossible to reverse and which have a serious impact on functionality. Their consequences[2] are disabling for the exposed individual and severely affect his physical behaviour, his bodily functions and/or his relations with other individuals.

The list that follows divides the major deterministic effects into three groups according to the classification adopted. It includes not only the effects on exposed individuals but also teratogenic effects, i.e. the effects of irradiation on the embryo and the foetus during pregnancy (in italics).

Non-lethal non-disabling effects

Vomiting[3]
Diarrhoea[3]
Hypothyroidism
Thyroiditis
Skin burns[3]

Non-lethal disabling effects

Interruption of ovogenesis
Interruption of spermatogenesis
Cataract
Pulmonary fibrosis
Severe mental retardation
Microcephaly

[2] Lesion and/or functional symptom that persists after a patient has been cured or after injury (Larousse dictionary 2000).

[3] This non-disabling effect may, in some cases, be a precursor and therefore indicator of a more serious deterministic effect.

Lethal effects

Bone marrow irradiation syndrome

Pulmonary irradiation syndrome

Gastro-intestinal syndrome

Death of the embryo

1.2. Threshold and frequency of occurrence of deterministic effects

At present, there is a scientific consensus on the existence of threshold doses below which deterministic effects never occur. Each deterministic effect has its own threshold value.

Below this threshold, morphological and functional modifications in tissues are reversible. Indeed, the stem cells, which are intact, gradually repopulate the damaged tissue. Beyond this threshold, the frequency of the effect, the time it takes to become apparent, and even its severity increase as the dose increases for a given population.

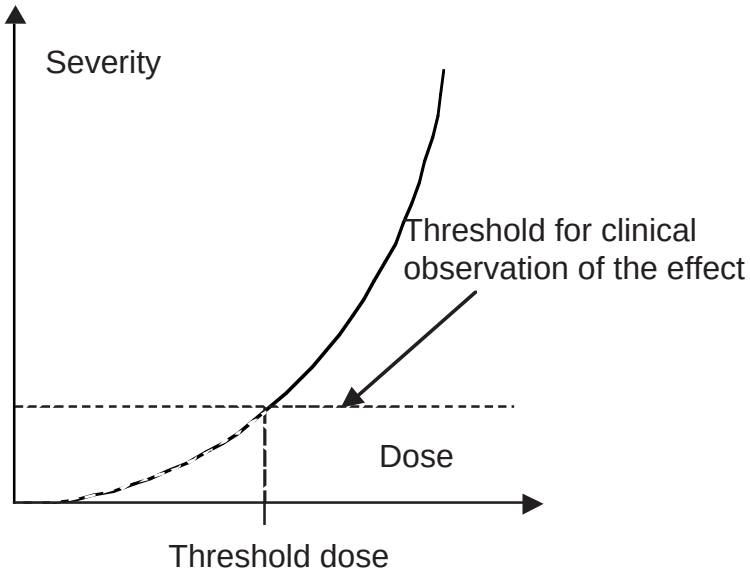


Figure A. Variation of severity of effect as a function of dose

At the scale of an entire population, deterministic effects do not occur in a random manner. Threshold doses are distributed within a population according to a sigmoidal

relationship (linear coordinates), with the effect becoming more frequent as the dose increases and frequency tending towards zero as the dose decreases.

The upper part of Figure B below shows how the frequency of a particular deterministic effect, defined as a clinically recognisable pathological condition, increases as a function of dose in a population of individuals with varying degrees of sensitivity to radiation.

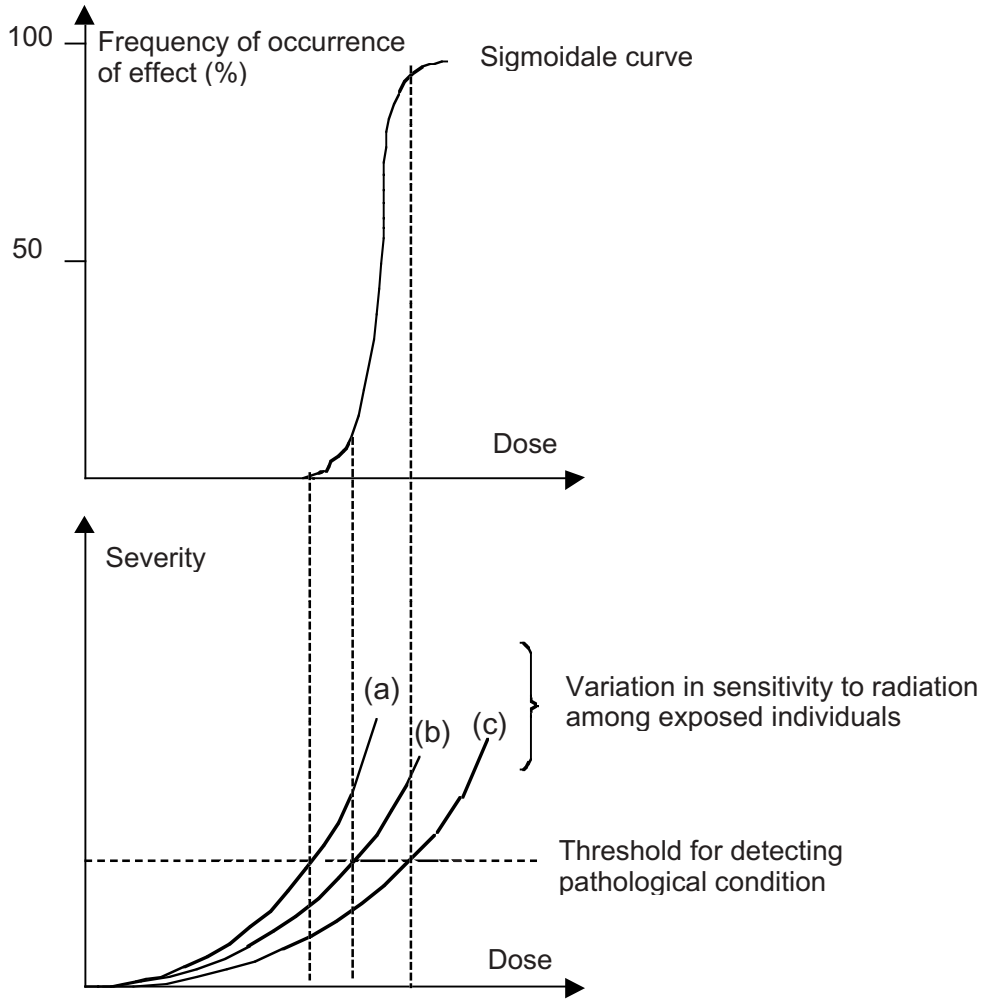


Figure B. Plotting the dose-frequency curve

The lower part of Figure B shows the dose-severity relationship for a population with, to simplify matters, three levels of sensitivity to radiation. The pathological state detection limit is reached at a lower dose in the group containing the most sensitive individuals (Curve a) than in the two least sensitive groups (Curves b and c).

From the upper part of Figure B, we can therefore determine dose values D_5, D_{50} and D_{100} such that 5%, 50% and 100% of the irradiated population develops the deterministic effect in question.

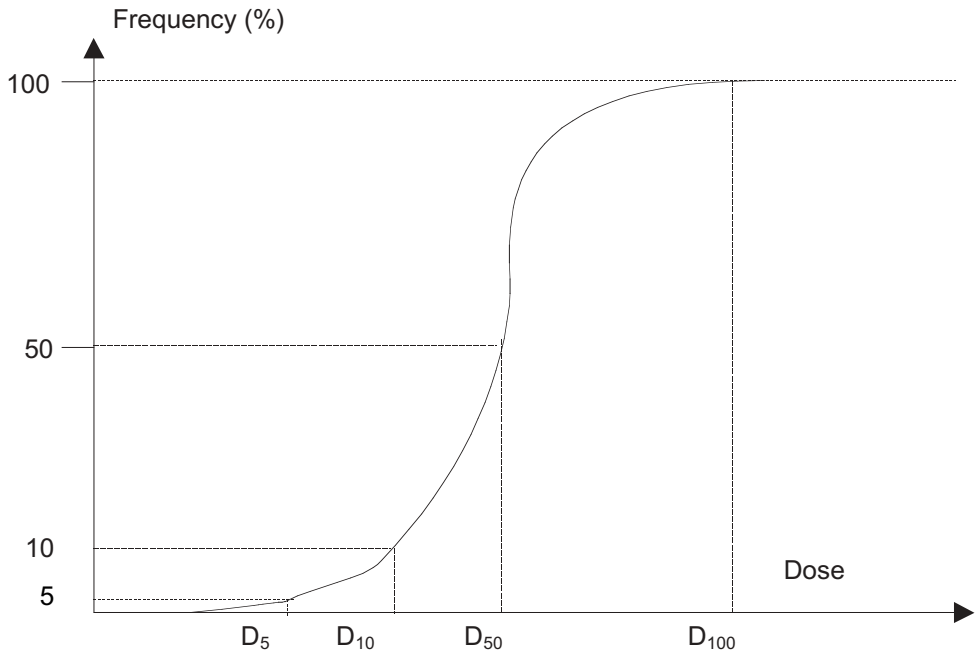


Figure C. Percentage of the population exhibiting the effect

The threshold value varies according to:

- The effect in question, which is directly associated with the sensitivity to radiation of the irradiated organ and/or tissue.
- The distribution of the dose over time, i.e. the dose rate.

1.3. Calculating the probability of occurrence of the effect using the NRPB model

In 1996, the National Radiological Protection Board (NRPB) published a report on deterministic effects in which it described a risk calculation model that made allowance for all the information available to date.

In this report, the risk for a given population is expressed as follows:

$$R = 1 - e^{-H} \qquad (1)$$

where the chance function H is estimated thus:

$$H = ln\,2.\int\left(\frac{\dot{D}dt}{D_{50}(\dot{D})}\right)^{\nu} \qquad (2)$$

where

$\dot{D}$: dose rate in Sv/h
D_{50} : dose at which 50% of the exposed population develops the effect
ν : adjustment factor

the equation can be reduced to:

$$H = \ln 2.\left(\frac{D}{D_{50}}\right)^{\nu} \qquad (3)$$

when dose rate $\dot{D}$ is constant.

The relationship between D_{50} and dose rate $\dot{D}$ in Gy/h is given by:

$$D_{50}(\dot{D}) = \theta_{\infty} + \frac{\theta_1}{\dot{D}} \qquad (4)$$

where

θ_{∞} : value in Gy of D_{50} for instantaneous exposure (infinite dose rate)

θ_1 : in Gy^2/h which represents the increase in D_{50} as the dose rate decreases

Important: The probabilities of occurrence of deterministic effects given in Part II of this appendix are only valid for low energy transfer rays such as photons. For some effects and for high energy transfer rays (alpha particles and neutrons), *D* should be

replaced by $RBE^{4} \times D$ in Equation (3) and $\dot{D}$ by $RBE \times \dot{D}$ in Equation (4). The RBE (NRPB) values to be applied for the highest linear energy transfer rays (alpha particles and neutrons) are given in Part II of this appendix.

The parameter values used are those recommended by the NRPB. The tables and figures in Part II of this appendix correspond to these parameter values. If other more recent or more consensual values were to be adopted, the corresponding risk calculations would have to be repeated. This would not call into question the principles whereby the scales mentioned previously were created.

1.4. Variation in risk threshold as a function of dose rate

As can be seen in the details of the risk calculations described above, the dose rate affects the frequency of occurrence of a deterministic effect within an irradiated population; it also affects the threshold level.

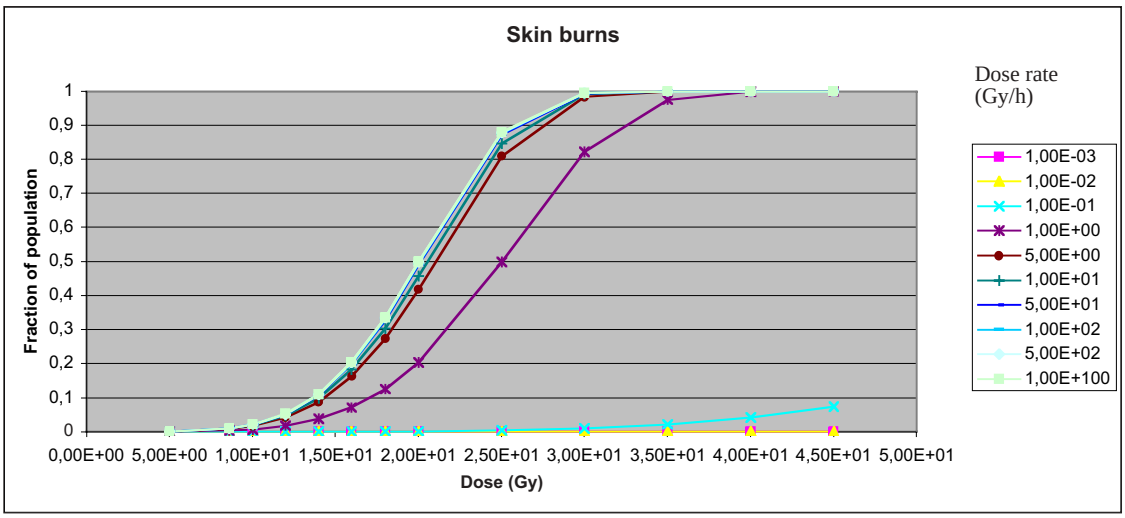
The absolute threshold for a precise deterministic effect is given in the tables (NRPB) for an infinite dose rate (D_{∞}) and a “flash” dose. A reduction in dose rate, for a constant dose, leads to a reduction in:

- the absolute threshold,
- the frequency of occurrence of the effect in question,
- an increase in the latency time between exposure and clinical signs of the effect.

This is why it is useful to have charts showing the frequency of occurrence of given effects at precise doses and dose rates.

[4] RBE: Relative Biological Effectiveness

Example: If the effect of burns to the skin is considered, D_{10} = 13.7 Gy is obtained for an infinite dose rate (light green curve) but for a dose rate of 1 Gy/h (purple curve), the probability of occurrence of the effect in 10% of the population concerned corresponds to a dose of around 17.2 Gy (D_{10}= 17.2 Gy).



This graph shows the variation in frequency of occurrence of skin burns in the population according to dose and dose rate.

2. CHARTS USED TO DETERMINE RISK FOR A GIVEN DETERMINISTIC EFFECT, DOSE AND DOSE RATE

The curves and associated tables in this report can be used to determine risk (i.e. the probability of occurrence of a given deterministic effect in a given organ) for an individual as a function of the dose received and the dose rate to which he was exposed.

In order to make it easier to understand the information given concerning exposure to the severity levels indicated on the scale, the areas corresponding to the probabilities of occurrence of the effects used for the scale are shown in different colours.

The area in which the probability of occurrence of the effect is less than 1% has not been shaded.

The area in which the probability of occurrence of the effect is between 1% and 5% is shown in yellow.

The area in which the probability of occurrence of the effect is between 5% and 50% is shown in light orange.

The area in which the probability of occurrence of the effect is at least 50% is shown in dark orange.

Risk level D_5 and D_{50} are shown because they are used as boundaries in the system proposed in this report for determining the severity level of an exposure event. A table summarising the values of D_1, D_5, D_{50} and D_{100} for the various types of deterministic effects can be found in Section 2.4.

2.1. Non-lethal non-disabling effects

2.1.1. Vomiting and diarrhoea

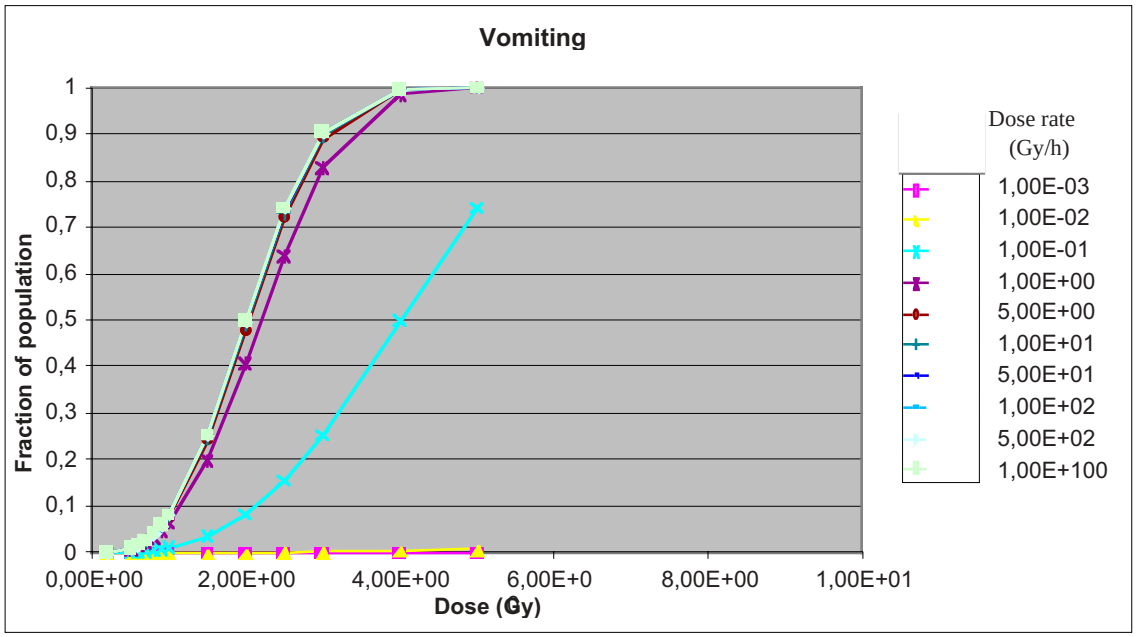
These two effects are part of a group of associated symptoms known as the **"prodromal phase"** of acute radiation sickness. This phase includes symptoms of acute gastro-intestinal effects (anorexia, nausea, vomiting, diarrhoea, intestinal pain and salivation), which may be accompanied by nervous symptoms (fatigue, headache, apathy and perspiration). This is a temporary phase and occurs about two hours after brief irradiation of the abdomen (threshold of around 0.5 Gy).

Vomiting

θ_8 Gy	θ_1 Gy^2/h	ν	RBE (alpha)	D_1 Gy
2	0.2	3	-	0.49

Dose (Gy) / Dose rate (Gy/h)	2,00E-01	5,00E-01	6,00E-01	7,00E-01	8,00E-01	9,00E-01	1,00E+00	1,50E+00	2,00E+00	2,50E+00	3,00E+00	4,00E+00	5,00E+00
1,00E-03	6,73E-10	1,05E-08	1,82E-08	2,88E-08	4,31E-08	6,13E-08	8,41E-08	2,84E-07	6,73E-07	1,31E-06	2,27E-06	5,38E-06	1,05E-05
1,00E-02	5,21E-07	8,14E-06	1,41E-05	2,23E-05	3,33E-05	4,75E-05	6,51E-05	2,20E-04	5,21E-04	1,02E-03	1,76E-03	4,16E-03	8,10E-03
1,00E-01	8,66E-05	1,35E-03	2,34E-03	3,71E-03	5,53E-03	7,86E-03	1,08E-02	3,59E-02	8,30E-02	1,56E-01	2,54E-01	5,00E-01	7,42E-01
1,00E+00	5,21E-04	8,10E-03	1,40E-02	2,21E-02	3,28E-02	4,63E-02	6,30E-02	1,97E-01	4,06E-01	6,38E-01	8,28E-01	9,84E-01	1,00E+00
5,00E+00	6,53E-04	1,02E-02	1,75E-02	2,76E-02	4,09E-02	5,78E-02	7,84E-02	2,41E-01	4,80E-01	7,21E-01	8,90E-01	9,95E-01	1,00E+00
1,00E+01	6,73E-04	1,05E-02	1,80E-02	2,84E-02	4,21E-02	5,95E-02	8,07E-02	2,47E-01	4,90E-01	7,31E-01	8,97E-01	9,95E-01	1,00E+00
5,00E+01	6,89E-04	1,07E-02	1,84E-02	2,91E-02	4,31E-02	6,09E-02	8,25E-02	2,52E-01	4,98E-01	7,40E-01	9,02E-01	9,96E-01	1,00E+00
1,00E+02	6,91E-04	1,07E-02	1,85E-02	2,92E-02	4,33E-02	6,10E-02	8,28E-02	2,53E-01	4,99E-01	7,41E-01	9,03E-01	9,96E-01	1,00E+00
5,00E+02	6,92E-04	1,08E-02	1,85E-02	2,93E-02	4,34E-02	6,12E-02	8,29E-02	2,53E-01	5,00E-01	7,42E-01	9,03E-01	9,96E-01	1,00E+00
1,00E+100	6,93E-04	1,08E-02	1,85E-02	2,93E-02	4,34E-02	6,12E-02	8,30E-02	2,54E-01	5,00E-01	7,42E-01	9,04E-01	9,96E-01	1,00E+00

>D1
>D5
>D50

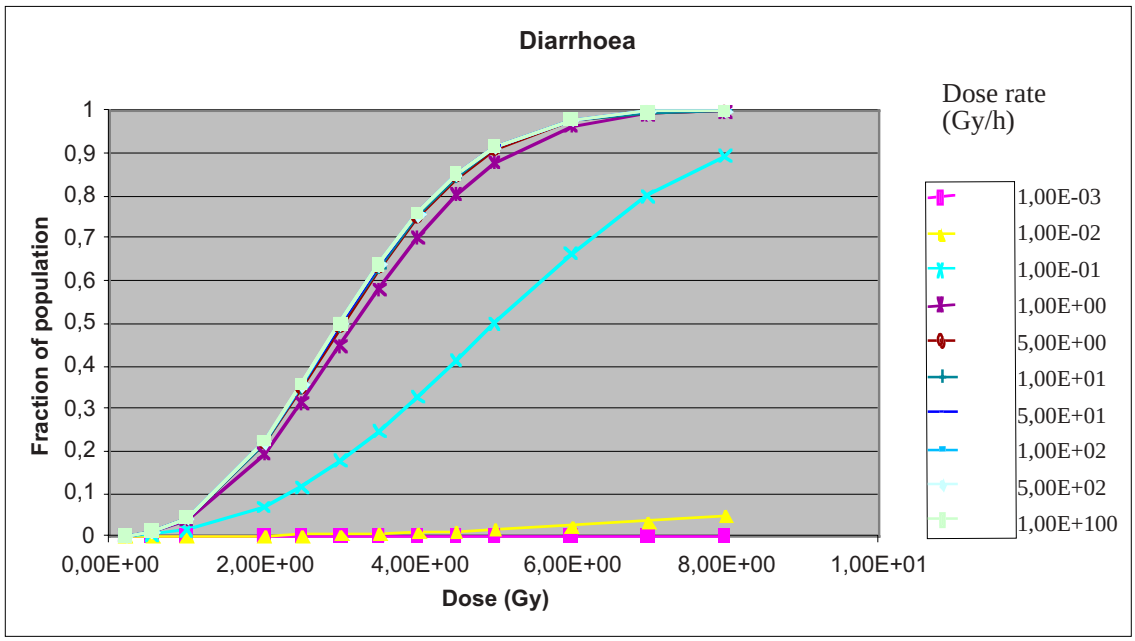


Diarrhoea

θ_8 Gy	θ_1 Gy^2/h	ν	RBE (alpha)	D_1 Gy
3	0.2	2.5	-	0.55

Dose (Gy) / Dose rate (Gy/h)	2,00E-01	5,50E-01	1,00E+00	2,00E+00	2,50E+00	3,00E+00	3,50E+00	4,00E+00	4,50E+00	5,00E+00	6,00E+00	7,00E+00	8,00E+00
1,00E-03	2,11E-08	2,65E-07	1,18E-06	6,68E-06	1,17E-05	1,84E-05	2,71E-05	3,78E-05	5,07E-05	6,60E-05	1,04E-04	1,53E-04	2,14E-04
1,00E-02	4,89E-06	6,13E-05	2,73E-04	1,54E-03	2,70E-03	4,25E-03	6,24E-03	8,70E-03	1,17E-02	1,52E-02	2,38E-02	3,48E-02	4,83E-02
1,00E-01	2,22E-04	2,78E-03	1,23E-02	6,77E-02	1,15E-01	1,76E-01	2,47E-01	3,28E-01	4,13E-01	5,00E-01	6,65E-01	8,00E-01	8,94E-01
1,00E+00	6,77E-04	8,45E-03	3,71E-02	1,93E-01	3,12E-01	4,46E-01	5,80E-01	7,02E-01	8,03E-01	8,79E-01	9,64E-01	9,93E-01	9,99E-01
5,00E+00	7,69E-04	9,60E-03	4,21E-02	2,16E-01	3,46E-01	4,89E-01	6,27E-01	7,48E-01	8,42E-01	9,10E-01	9,77E-01	9,96E-01	1,00E+00
1,00E+01	7,82E-04	9,76E-03	4,28E-02	2,19E-01	3,51E-01	4,94E-01	6,33E-01	7,53E-01	8,47E-01	9,13E-01	9,79E-01	9,97E-01	1,00E+00
5,00E+01	7,92E-04	9,89E-03	4,33E-02	2,22E-01	3,55E-01	4,99E-01	6,38E-01	7,58E-01	8,51E-01	9,16E-01	9,80E-01	9,97E-01	1,00E+00
1,00E+02	7,94E-04	9,91E-03	4,34E-02	2,22E-01	3,55E-01	4,99E-01	6,38E-01	7,58E-01	8,51E-01	9,16E-01	9,80E-01	9,97E-01	1,00E+00
5,00E+02	7,95E-04	9,92E-03	4,35E-02	2,22E-01	3,55E-01	5,00E-01	6,39E-01	7,59E-01	8,52E-01	9,17E-01	9,80E-01	9,97E-01	1,00E+00
1,00E+100	7,95E-04	9,93E-03	4,35E-02	2,22E-01	3,56E-01	5,00E-01	6,39E-01	7,59E-01	8,52E-01	9,17E-01	9,80E-01	9,97E-01	1,00E+00

>D1
>D5
>D50



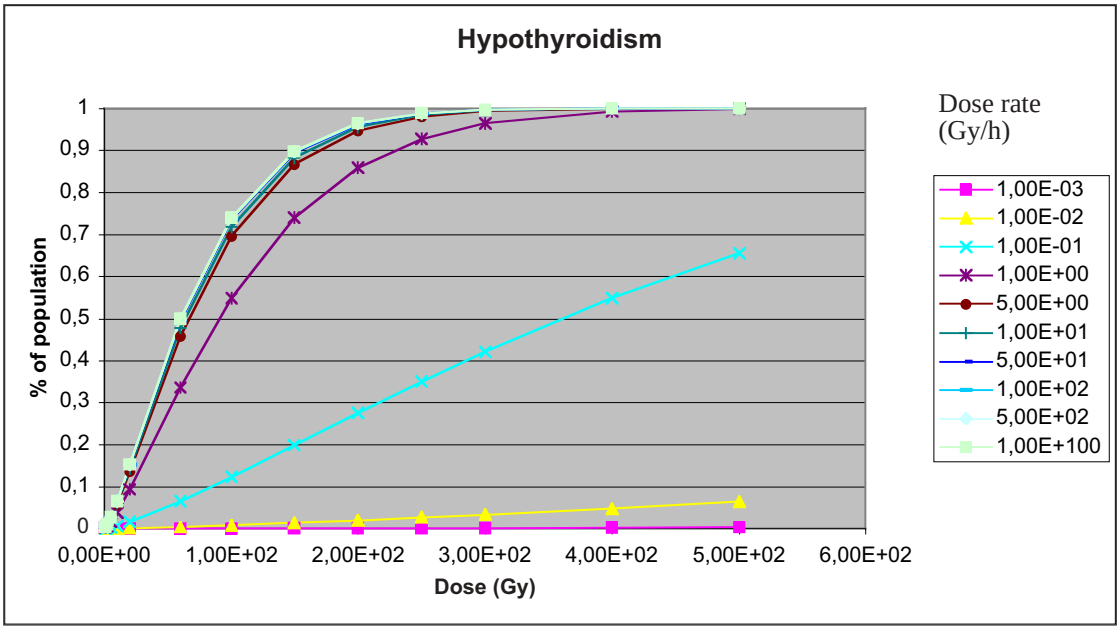
2.1.2. Hypothyroidism

Hypothyroidism is the result of inadequate amounts of thyroid hormone. The thyroid can no longer perform its function, i.e. maintain metabolic processes at their correct rate by producing thyroid hormones. The symptoms are fatigue, reduced resistance to cold, mental apathy, body fluid retention, muscular cramps and a general reduction in body functions. The threshold at which effects occur would appear to be 2.3 Gy to the thyroid. Hormone treatment is given orally.

θ_8 Gy	θ_1 Gy^2/h	ν	RBE (alpha)	D_1 Gy
60	30	1.3	-	2.3

Dose (Gy) / Dose rate (Gy/h)	1,00E+00	2,30E+00	5,00E+00	1,00E+01	2,00E+01	6,00E+01	1,00E+02	1,50E+02	2,00E+02	2,50E+02	3,00E+02	4,00E+02	5,00E+02
1,00E-03	1,05E-06	3,09E-06	8,47E-06	2,09E-05	5,14E-05	2,14E-04	4,16E-04	7,05E-04	1,02E-03	1,37E-03	1,74E-03	2,52E-03	3,37E-03
1,00E-02	2,04E-05	6,02E-05	1,65E-04	4,07E-04	1,00E-03	4,17E-03	8,08E-03	1,37E-02	1,98E-02	2,64E-02	3,33E-02	4,80E-02	6,37E-02
1,00E-01	3,29E-04	9,72E-04	2,67E-03	6,55E-03	1,60E-02	6,53E-02	1,23E-01	1,99E-01	2,76E-01	3,50E-01	4,21E-01	5,48E-01	6,54E-01
1,00E+00	1,99E-03	5,88E-03	1,60E-02	3,91E-02	9,34E-02	3,36E-01	5,48E-01	7,40E-01	8,59E-01	9,27E-01	9,64E-01	9,92E-01	9,98E-01
5,00E+00	2,98E-03	8,79E-03	2,39E-02	5,79E-02	1,37E-01	4,58E-01	6,96E-01	8,67E-01	9,47E-01	9,80E-01	9,93E-01	9,99E-01	1,00E+00
1,00E+01	3,17E-03	9,33E-03	2,54E-02	6,14E-02	1,44E-01	4,78E-01	7,17E-01	8,82E-01	9,55E-01	9,84E-01	9,95E-01	1,00E+00	1,00E+00
5,00E+01	3,33E-03	9,81E-03	2,67E-02	6,45E-02	1,51E-01	4,96E-01	7,35E-01	8,95E-01	9,62E-01	9,87E-01	9,96E-01	1,00E+00	1,00E+00
1,00E+02	3,35E-03	9,87E-03	2,69E-02	6,49E-02	1,52E-01	4,98E-01	7,38E-01	8,96E-01	9,63E-01	9,88E-01	9,96E-01	1,00E+00	1,00E+00
5,00E+02	3,37E-03	9,93E-03	2,70E-02	6,52E-02	1,53E-01	5,00E-01	7,39E-01	8,98E-01	9,64E-01	9,88E-01	9,96E-01	1,00E+00	1,00E+00
1,00E+100	3,38E-03	9,94E-03	2,70E-02	6,53E-02	1,53E-01	5,00E-01	7,40E-01	8,98E-01	9,64E-01	9,88E-01	9,96E-01	1,00E+00	1,00E+00

>D1
>D5
>D50



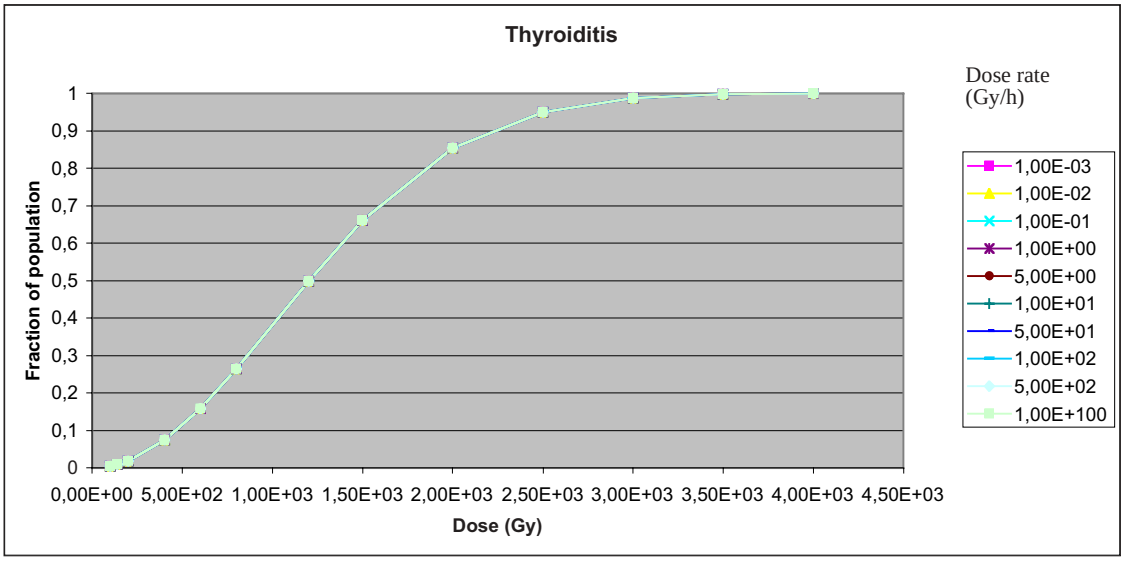
2.1.3. Thyroiditis

Thyroiditis is inflammation of the thyroid gland due to necrosis of a number of thyroid cells (or all the cells, as the case may be). The first symptoms of radiation-induced thyroiditis appear within two weeks of irradiation and include pain and stiffness in the neck. This inflammation sometimes results in the release of thyroid hormones into the bloodstream, causing thyrotoxicity. The threshold adopted for this effect is a committed dose of 140 Gy to the thyroid. This dose level can only be reached in the case of external exposure, with no irradiation of the bone marrow. In this case, the prognosis as to survival would be called into question (see Section 2.3.1 above). Thyroiditis can only occur in isolation in the case of internal exposure.

θ_8 Gy	θ_1 Gy^2/h	ν	RBE (alpha)	D_1 Gy
1200	0	2	-	140

Dose (Gy) / Dose rate (Gy/h)	1,00E+02	1,40E+02	2,00E+02	4,00E+02	6,00E+02	8,00E+02	1,20E+03	1,50E+03	2,00E+03	2,50E+03	3,00E+03	3,50E+03	4,00E+03
1,00E-03	4,80E-03	9,39E-03	1,91E-02	7,41E-02	1,59E-01	2,65E-01	5,00E-01	6,61E-01	8,54E-01	9,51E-01	9,87E-01	9,97E-01	1,00E+00
1,00E-02	4,80E-03	9,39E-03	1,91E-02	7,41E-02	1,59E-01	2,65E-01	5,00E-01	6,61E-01	8,54E-01	9,51E-01	9,87E-01	9,97E-01	1,00E+00
1,00E-01	4,80E-03	9,39E-03	1,91E-02	7,41E-02	1,59E-01	2,65E-01	5,00E-01	6,61E-01	8,54E-01	9,51E-01	9,87E-01	9,97E-01	1,00E+00
1,00E+00	4,80E-03	9,39E-03	1,91E-02	7,41E-02	1,59E-01	2,65E-01	5,00E-01	6,61E-01	8,54E-01	9,51E-01	9,87E-01	9,97E-01	1,00E+00
5,00E+00	4,80E-03	9,39E-03	1,91E-02	7,41E-02	1,59E-01	2,65E-01	5,00E-01	6,61E-01	8,54E-01	9,51E-01	9,87E-01	9,97E-01	1,00E+00
1,00E+01	4,80E-03	9,39E-03	1,91E-02	7,41E-02	1,59E-01	2,65E-01	5,00E-01	6,61E-01	8,54E-01	9,51E-01	9,87E-01	9,97E-01	1,00E+00
5,00E+01	4,80E-03	9,39E-03	1,91E-02	7,41E-02	1,59E-01	2,65E-01	5,00E-01	6,61E-01	8,54E-01	9,51E-01	9,87E-01	9,97E-01	1,00E+00
1,00E+02	4,80E-03	9,39E-03	1,91E-02	7,41E-02	1,59E-01	2,65E-01	5,00E-01	6,61E-01	8,54E-01	9,51E-01	9,87E-01	9,97E-01	1,00E+00
5,00E+02	4,80E-03	9,39E-03	1,91E-02	7,41E-02	1,59E-01	2,65E-01	5,00E-01	6,61E-01	8,54E-01	9,51E-01	9,87E-01	9,97E-01	1,00E+00
1,00E+100	4,80E-03	9,39E-03	1,91E-02	7,41E-02	1,59E-01	2,65E-01	5,00E-01	6,61E-01	8,54E-01	9,51E-01	9,87E-01	9,97E-01	1,00E+00

>D1
>D5
>D50



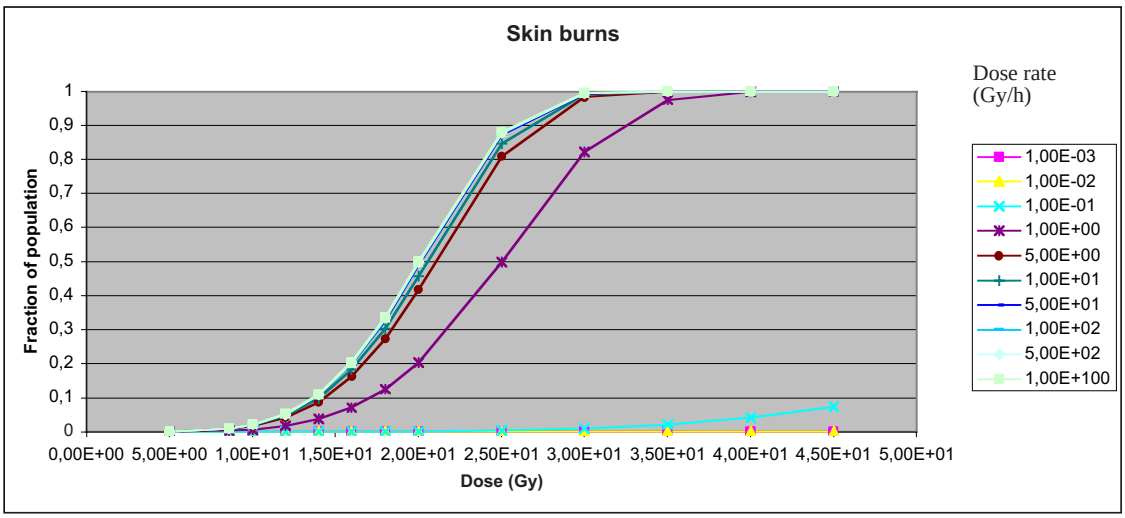
2.1.4. Superficial skin burns (erythema, oedema)

These skin conditions appear within a few hours of exposure, are temporary and result in dilation of the blood capillaries. The threshold dose resulting from the NRPB calculations is 8.6 Gy. These conditions may disappear or, in some cases, be followed, three to five days later, by secondary erythema, blisters and, more seriously, skin desquamation similar to that which would occur with second degree burns. Should the exposure become chronic, other effects may appear on the skin such as the disappearance of fingerprints, dryness, atrophy and hyperkeratosis. Age is one factor that affects the frequency of occurrence of skin effects. Young people are less sensitive than the elderly.

θ_8 Gy	θ_1 Gy^2/h	ν	RBE (alpha)	D_1 Gy
20	5	5	-	8.6

Dose (Gy) / Dose rate (Gy/h)	5,00E+00	8,60E+00	1,00E+01	1,20E+01	1,40E+01	1,60E+01	1,80E+01	2,00E+01	2,50E+01	3,00E+01	3,50E+01	4,00E+01	4,50E+01
1,00E-03	6,66E-16	1,02E-14	2,18E-14	5,41E-14	1,17E-13	2,28E-13	4,11E-13	6,96E-13	2,12E-12	5,28E-12	1,14E-11	2,23E-11	4,01E-11
1,00E-02	5,70E-11	8,58E-10	1,82E-09	4,54E-09	9,81E-09	1,91E-08	3,44E-08	5,83E-08	1,78E-07	4,43E-07	9,58E-07	1,87E-06	3,36E-06
1,00E-01	1,29E-06	1,94E-05	4,12E-05	1,03E-04	2,22E-04	4,32E-04	7,79E-04	1,32E-03	4,02E-03	9,97E-03	2,14E-02	4,14E-02	7,33E-02
1,00E+00	2,22E-04	3,33E-03	7,07E-03	1,75E-02	3,75E-02	7,17E-02	1,26E-01	2,03E-01	5,00E-01	8,22E-01	9,76E-01	9,99E-01	1,00E+00
5,00E+00	5,30E-04	7,95E-03	1,68E-02	4,14E-02	8,72E-02	1,63E-01	2,74E-01	4,19E-01	8,09E-01	9,84E-01	1,00E+00	1,00E+00	1,00E+00
1,00E+01	5,98E-04	8,97E-03	1,90E-02	4,65E-02	9,78E-02	1,82E-01	3,04E-01	4,58E-01	8,46E-01	9,90E-01	1,00E+00	1,00E+00	1,00E+00
5,00E+01	6,60E-04	9,89E-03	2,09E-02	5,12E-02	1,07E-01	1,99E-01	3,29E-01	4,91E-01	8,73E-01	9,94E-01	1,00E+00	1,00E+00	1,00E+00
1,00E+02	6,68E-04	1,00E-02	2,12E-02	5,18E-02	1,09E-01	2,01E-01	3,33E-01	4,96E-01	8,76E-01	9,94E-01	1,00E+00	1,00E+00	1,00E+00
5,00E+02	6,75E-04	1,01E-02	2,14E-02	5,23E-02	1,10E-01	2,03E-01	3,35E-01	4,99E-01	8,79E-01	9,95E-01	1,00E+00	1,00E+00	1,00E+00
1,00E+100	6,77E-04	1,01E-02	2,14E-02	5,25E-02	1,10E-01	2,03E-01	3,36E-01	5,00E-01	8,79E-01	9,95E-01	1,00E+00	1,00E+00	1,00E+00

>D1
>D5
>D50



2.2. Non-lethal disabling effects

2.2.1. Interruption of spermatogenesis

The testis are one of the organs that are the most sensitive to radiation. Male gametes are produced throughout adult life, starting in adolescence. The cells that are the most sensitive to radiation are those that are dividing just before they reach their maturity. Spermatogonia, which are produced earlier, are more resistant.

As our scientific knowledge stands at present, it is agreed that doses of 0.1 to 0.3 Gy result in temporary oligospermia (a reduction of the number of sperm cells in the ejaculate). Higher doses result in temporary aspermia (absence of ejaculated semen), which lasts no more than two years (if the source of exposure is removed). Doses of more than 2 Gy result in permanent aspermia.

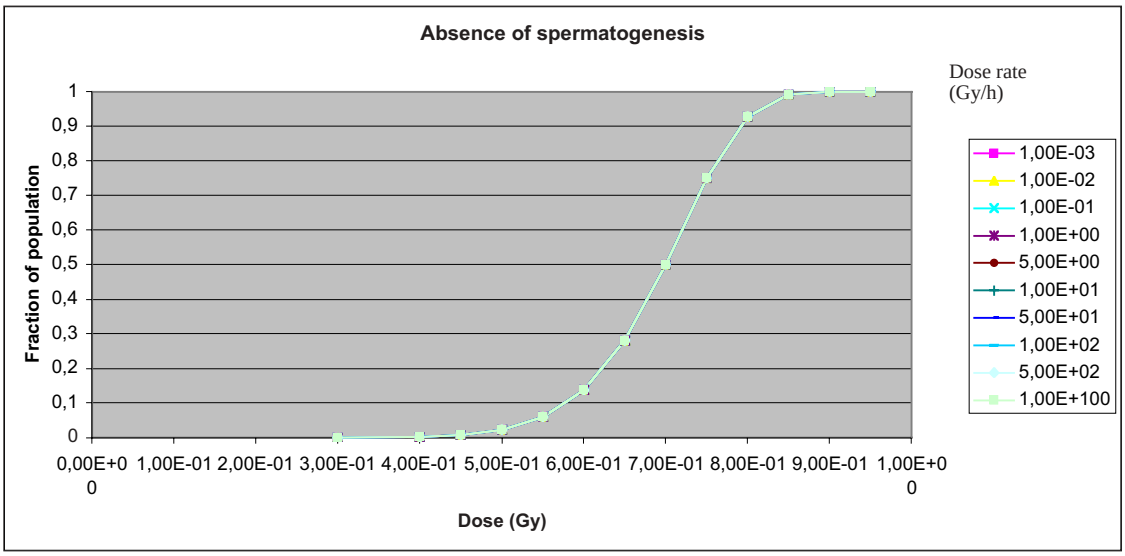
The NRPB model describes the onset of temporary interruption of spermatogenesis. The threshold value is 0.46 Gy, given that chronic exposure is more harmful than acute exposure. No models exist for oligospermia or permanent aspermia.

θ_8 Gy	θ_1 Gy^2/h	ν	RBE (alpha)	D_1 Gy
0.7	0	10	-	0.46*

* ICRP Publication 60 gives 0.15 (temporary sterility) and 3.5 - 6 (permanent sterility, according to UNSCEAR's 1998 report)

Dose (Gy) / Dose rate (Gy/h)	3,00E-01	4,00E-01	4,50E-01	5,00E-01	5,50E-01	6,00E-01	6,50E-01	7,00E-01	7,50E-01	8,00E-01	8,50E-01	9,00E-01	9,50E-01
1,00E-03	1,45E-04	2,57E-03	8,32E-03	2,37E-02	6,03E-02	1,38E-01	2,81E-01	5,00E-01	7,49E-01	9,28E-01	9,92E-01	1,00E+00	1,00E+00
1,00E-02	1,45E-04	2,57E-03	8,32E-03	2,37E-02	6,03E-02	1,38E-01	2,81E-01	5,00E-01	7,49E-01	9,28E-01	9,92E-01	1,00E+00	1,00E+00
1,00E-01	1,45E-04	2,57E-03	8,32E-03	2,37E-02	6,03E-02	1,38E-01	2,81E-01	5,00E-01	7,49E-01	9,28E-01	9,92E-01	1,00E+00	1,00E+00
1,00E+00	1,45E-04	2,57E-03	8,32E-03	2,37E-02	6,03E-02	1,38E-01	2,81E-01	5,00E-01	7,49E-01	9,28E-01	9,92E-01	1,00E+00	1,00E+00
5,00E+00	1,45E-04	2,57E-03	8,32E-03	2,37E-02	6,03E-02	1,38E-01	2,81E-01	5,00E-01	7,49E-01	9,28E-01	9,92E-01	1,00E+00	1,00E+00
1,00E+01	1,45E-04	2,57E-03	8,32E-03	2,37E-02	6,03E-02	1,38E-01	2,81E-01	5,00E-01	7,49E-01	9,28E-01	9,92E-01	1,00E+00	1,00E+00
5,00E+01	1,45E-04	2,57E-03	8,32E-03	2,37E-02	6,03E-02	1,38E-01	2,81E-01	5,00E-01	7,49E-01	9,28E-01	9,92E-01	1,00E+00	1,00E+00
1,00E+02	1,45E-04	2,57E-03	8,32E-03	2,37E-02	6,03E-02	1,38E-01	2,81E-01	5,00E-01	7,49E-01	9,28E-01	9,92E-01	1,00E+00	1,00E+00
5,00E+02	1,45E-04	2,57E-03	8,32E-03	2,37E-02	6,03E-02	1,38E-01	2,81E-01	5,00E-01	7,49E-01	9,28E-01	9,92E-01	1,00E+00	1,00E+00
1,00E+100	1,45E-04	2,57E-03	8,32E-03	2,37E-02	6,03E-02	1,38E-01	2,81E-01	5,00E-01	7,49E-01	9,28E-01	9,92E-01	1,00E+00	1,00E+00

>D1
>D5
>D50



2.2.2. Interruption of ovogenesis

The ovaries are one of the organs that are the most sensitive to radiation. Unlike the male gamete production process, female gametes are produced discontinuously and the stock of stem cells is limited. Furthermore, the most mature cells are the most sensitive to radioactivity.

Doses of less than 0.6 Gy have no adverse effects on reproduction. Doses of between 1.5 and 5 Gy result in the temporary interruption of ovulation. A dose of 6 Gy (brief irradiation) or 10 Gy (dose spread over one week) is considered to result in the permanent interruption of ovulation in 100% of cases.

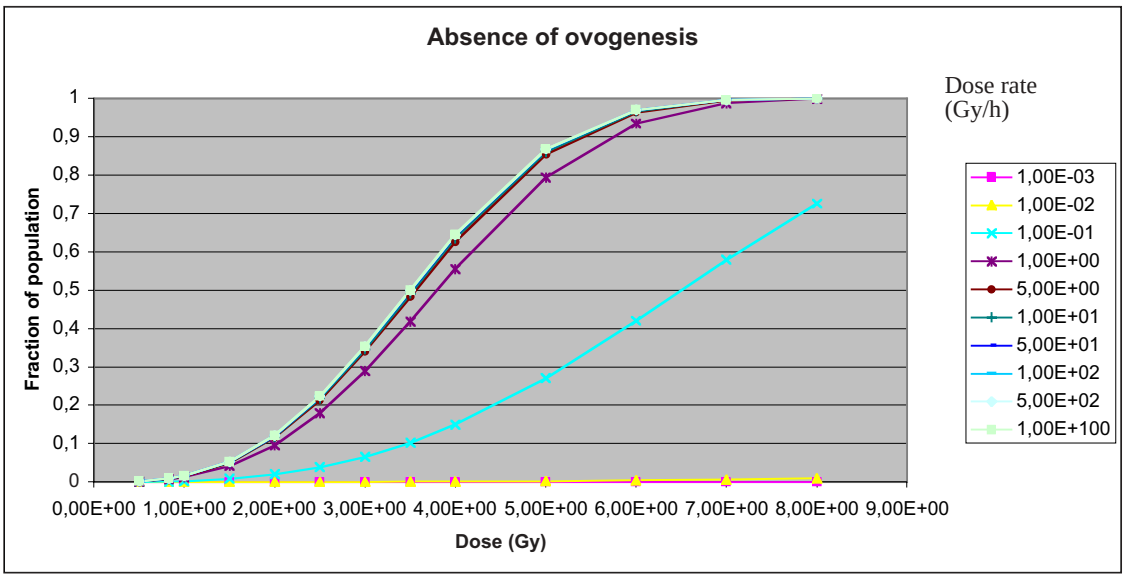
The only model available corresponds to the interruption of ovogenesis. The NRPB has opted for a value of between 0.8 and 0.9 Gy as the threshold value. The threshold value decreases with age, due to the lower number of stem cells available.

θ_8	θ_1	ν	RBE	D_1
Gy	Gy^2/h		(alpha)	Gy
3.5	0.3	3	-	0.85*

*ICRP Publication 60 gives 2.6 - 6 (sterility)

Dose (Gy) / Dose rate (Gy/h)	5,00E-01	8,30E-01	1,00E+00	1,50E+00	2,00E+00	2,50E+00	3,00E+00	3,50E+00	4,00E+00	5,00E+00	6,00E+00	7,00E+00	8,00E+00
1,00E-03	3,10E-09	1,42E-08	2,48E-08	8,37E-08	1,98E-07	3,87E-07	6,69E-07	1,06E-06	1,59E-06	3,10E-06	5,36E-06	8,50E-06	1,27E-05
1,00E-02	2,30E-06	1,05E-05	1,84E-05	6,22E-05	1,47E-04	2,88E-04	4,98E-04	7,90E-04	1,18E-03	2,30E-03	3,97E-03	6,30E-03	9,40E-03
1,00E-01	3,15E-04	1,44E-03	2,52E-03	8,48E-03	2,00E-02	3,87E-02	6,59E-02	1,03E-01	1,49E-01	2,71E-01	4,20E-01	5,79E-01	7,25E-01
1,00E+00	1,58E-03	7,20E-03	1,26E-02	4,17E-02	9,61E-02	1,79E-01	2,89E-01	4,18E-01	5,54E-01	7,94E-01	9,35E-01	9,87E-01	9,98E-01
5,00E+00	1,92E-03	8,75E-03	1,52E-02	5,05E-02	1,16E-01	2,13E-01	3,40E-01	4,82E-01	6,26E-01	8,53E-01	9,64E-01	9,95E-01	1,00E+00
1,00E+01	1,97E-03	8,97E-03	1,56E-02	5,18E-02	1,18E-01	2,18E-01	3,47E-01	4,91E-01	6,35E-01	8,61E-01	9,67E-01	9,96E-01	1,00E+00
5,00E+01	2,01E-03	9,15E-03	1,60E-02	5,28E-02	1,21E-01	2,22E-01	3,52E-01	4,98E-01	6,43E-01	8,66E-01	9,69E-01	9,96E-01	1,00E+00
1,00E+02	2,01E-03	9,18E-03	1,60E-02	5,30E-02	1,21E-01	2,23E-01	3,53E-01	4,99E-01	6,44E-01	8,67E-01	9,69E-01	9,96E-01	1,00E+00
5,00E+02	2,02E-03	9,20E-03	1,60E-02	5,31E-02	1,21E-01	2,23E-01	3,54E-01	5,00E-01	6,44E-01	8,67E-01	9,70E-01	9,96E-01	1,00E+00
1,00E+100	2,02E-03	9,20E-03	1,60E-02	5,31E-02	1,21E-01	2,23E-01	3,54E-01	5,00E-01	6,45E-01	8,67E-01	9,70E-01	9,96E-01	1,00E+00

>D1
>D5
>D50



2.2.3. Clouding and cataract

The lens of the eye is one of the tissues that are the most sensitive to radiation. After they have been exposed, the cells in the lens are damaged but continue to grow at a slower rate. Dead and damaged cells form a cloudy patch in the centre of the eye that, to begin with, has no effect on sight. Depending on the dose, this process continues until sight is impaired and may develop into the most recognisable and severe form, i.e. cataract.

The latency time can vary from a few months in the case of high doses to several years for lower doses. Once again, the dose rate and the chronicity of exposure are aggravating factors. In any case, at doses of more than 15 Gy, cataracts develop systematically, regardless of the breakdown of the dose over time.

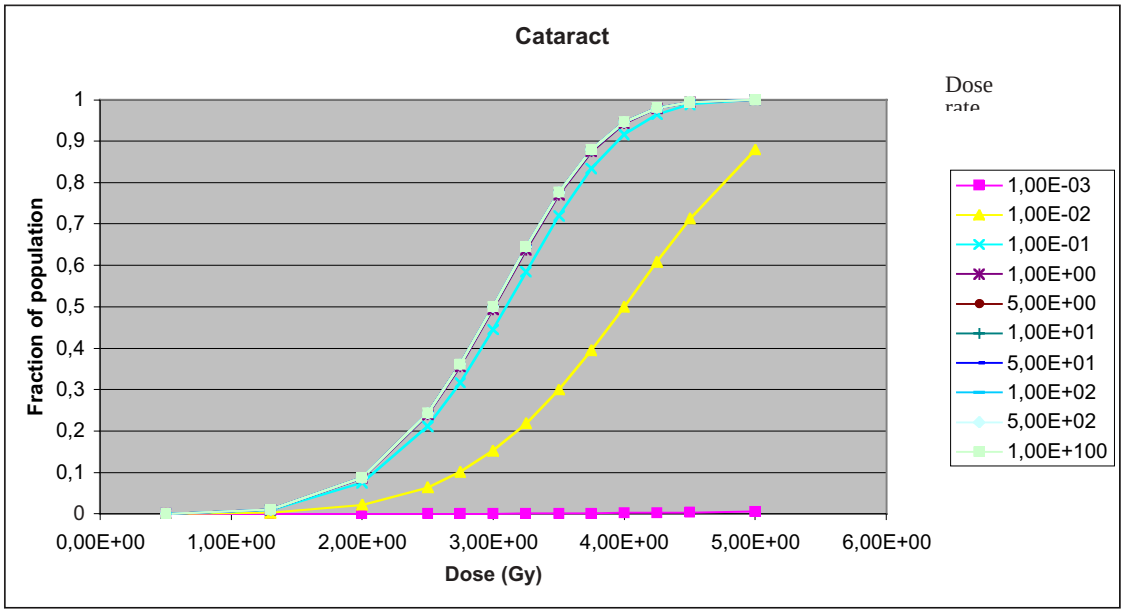
In view of our current knowledge, the threshold has been estimated at 1.3 Gy.

θ_8	θ_1	ν	RBE	D_1
Gy	Gy^2/h		(alpha)	Gy
3	0.01	5	-	1.3*

* ICRP Publication 60 gives 0.5 - 2 (opacity, according to Otake and Schull, 1990) and 2 - 10 (cataract, according to the NCRP's 1998 report)

Dose (Gy) / Dose rate (Gy/h)	5,00E-01	1,30E+00	2,00E+00	2,50E+00	2,75E+00	3,00E+00	3,25E+00	3,50E+00	3,75E+00	4,00E+00	4,25E+00	4,50E+00	5,00E+00
1,00E-03	5,83E-08	6,93E-06	5,97E-05	1,82E-04	2,94E-04	4,54E-04	6,77E-04	9,80E-04	1,38E-03	1,91E-03	2,59E-03	3,44E-03	5,82E-03
1,00E-02	2,12E-05	2,51E-03	2,14E-02	6,40E-02	1,01E-01	1,52E-01	2,18E-01	2,99E-01	3,95E-01	5,00E-01	6,09E-01	7,13E-01	8,79E-01
1,00E-01	7,57E-05	8,95E-03	7,46E-02	2,11E-01	3,17E-01	4,45E-01	5,84E-01	7,20E-01	8,34E-01	9,16E-01	9,65E-01	9,89E-01	9,99E-01
1,00E+00	8,77E-05	1,04E-02	8,59E-02	2,40E-01	3,57E-01	4,94E-01	6,38E-01	7,71E-01	8,75E-01	9,43E-01	9,80E-01	9,94E-01	1,00E+00
5,00E+00	8,88E-05	1,05E-02	8,70E-02	2,42E-01	3,61E-01	4,99E-01	6,43E-01	7,75E-01	8,79E-01	9,46E-01	9,81E-01	9,95E-01	1,00E+00
1,00E+01	8,90E-05	1,05E-02	8,71E-02	2,43E-01	3,61E-01	4,99E-01	6,44E-01	7,76E-01	8,79E-01	9,46E-01	9,81E-01	9,95E-01	1,00E+00
5,00E+01	8,91E-05	1,05E-02	8,72E-02	2,43E-01	3,61E-01	5,00E-01	6,44E-01	7,76E-01	8,79E-01	9,46E-01	9,81E-01	9,95E-01	1,00E+00
1,00E+02	8,91E-05	1,05E-02	8,72E-02	2,43E-01	3,61E-01	5,00E-01	6,44E-01	7,76E-01	8,79E-01	9,46E-01	9,81E-01	9,95E-01	1,00E+00
5,00E+02	8,91E-05	1,05E-02	8,72E-02	2,43E-01	3,61E-01	5,00E-01	6,45E-01	7,76E-01	8,79E-01	9,46E-01	9,81E-01	9,95E-01	1,00E+00
1,00E+100	8,91E-05	1,05E-02	8,72E-02	2,43E-01	3,61E-01	5,00E-01	6,45E-01	7,76E-01	8,79E-01	9,46E-01	9,81E-01	9,95E-01	1,00E+00

>D1
>D5
>D50



2.2.4. Pulmonary fibrosis

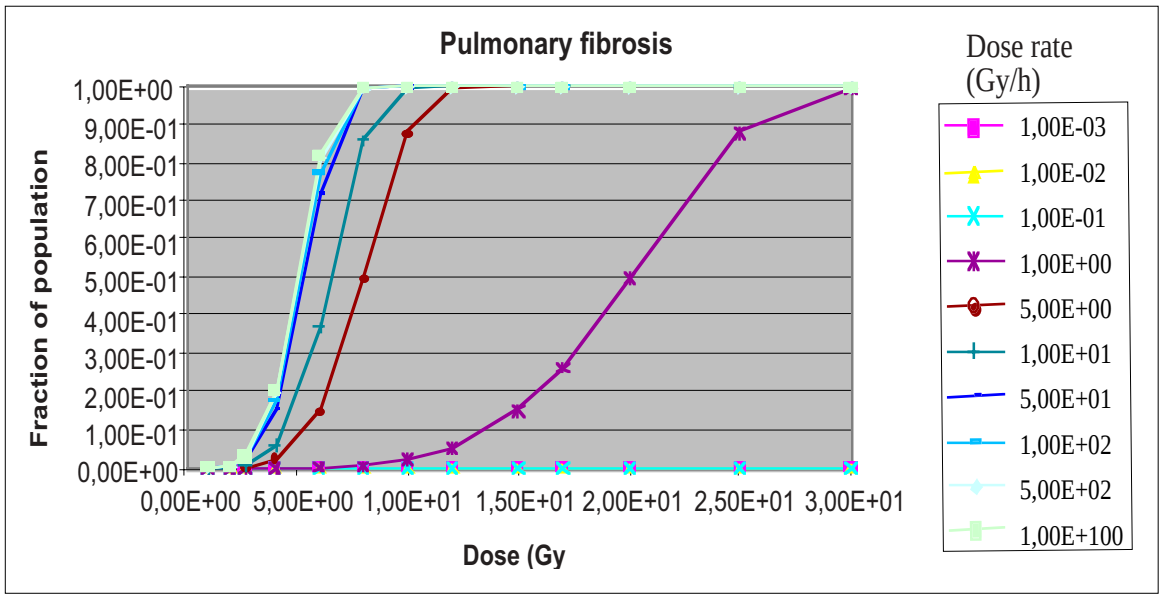
Irradiation of the lungs may cause fibrosis which results in a decrease in lung capacity, stiffness and a loss of elasticity of the pulmonary parenchymus, the direct consequences of which are the non-uniform distribution of gases and less effective gaseous exchanges in the pulmonary alveoli. Complications may be of a pulmonary or cardiovascular nature. The symptoms are hemoptysis (coughing up of blood) and acute respiratory insufficiency. The threshold recommended by the NRPB is 2.7 Gy.

In the case of internal contamination by an alpha emitter, the frequency of occurrence of pulmonary effects within a population increases. The relative biological effectiveness (RBE) is estimated at 7 for alpha radiation and the lungs, in relation to gamma radiation and X-rays.

θ_8 Gy	θ_1 Gy^2/h	ν	RBE (alpha)	D_1 Gy
5	15	5	7	2.7

Dose (Gy) / Dose rate (Gy/h)	1,00E+00	2,00E+00	2,70E+00	4,00E+00	6,00E+00	8,00E+00	1,00E+01	1,20E+01	1,50E+01	1,70E+01	2,00E+01	2,50E+01	3,00E+01
1,00E-03	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,11E-16	2,22E-16	6,66E-16	1,33E-15	2,89E-15	8,88E-15	2,21E-14
1,00E-02	1,11E-16	2,89E-15	1,29E-14	9,19E-14	6,98E-13	2,94E-12	8,98E-12	2,23E-11	6,82E-11	1,27E-10	2,87E-10	8,77E-10	2,18E-09
1,00E-01	7,75E-12	2,48E-10	1,11E-09	7,93E-09	6,02E-08	2,54E-07	7,75E-07	1,93E-06	5,88E-06	1,10E-05	2,48E-05	7,57E-05	1,88E-04
1,00E+00	2,17E-07	6,93E-06	3,11E-05	2,22E-04	1,68E-03	7,07E-03	2,14E-02	5,25E-02	1,52E-01	2,65E-01	5,00E-01	8,79E-01	9,95E-01
5,00E+00	2,12E-05	6,77E-04	3,03E-03	2,14E-02	1,52E-01	5,00E-01	8,79E-01	9,95E-01	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00
1,00E+01	5,97E-05	1,91E-03	8,54E-03	5,93E-02	3,72E-01	8,59E-01	9,97E-01	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00
5,00E+01	1,66E-04	5,29E-03	2,35E-02	1,56E-01	7,24E-01	9,96E-01	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00
1,00E+02	1,91E-04	6,10E-03	2,71E-02	1,78E-01	7,74E-01	9,98E-01	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00
5,00E+02	2,15E-04	6,86E-03	3,04E-02	1,98E-01	8,12E-01	9,99E-01	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00
1,00E+100	2,22E-04	7,07E-03	3,13E-02	2,03E-01	8,22E-01	9,99E-01	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00

>D1
>D5
>D50



2.2.5. Severe skin burns (ulceration and necrosis)

This section deals with the effects that appear as a result of irradiation that is more severe than that mentioned in Section 2.1.4 or during chronic exposure of the skin to ionising radiation.

Ulceration and necrosis are the most severe effects of irradiation of the skin. Necrosis is the final stage and lesions can only be repaired by plastic surgery. There are several types of necrosis. The least serious form is the result of cutaneous desquamation leading to a decrease in the number of stem cells in the basal membrane. At this stage, lesions can heal and a new thinner and more fragile skin can form which is usually depigmented. At higher doses (40 Gy), acute necrosis develops within two weeks. Cases of necrosis developing more than six months after exposure are described in the literature.

Generally speaking, the most severe cases of necrosis develop at doses such that it is hard to imagine them occurring without there being a fatal dose to the bone marrow. However, high doses in localised areas of the body may cause the same kind of damage. Furthermore, it is generally recognised that the surface area of the lesions is an important aspect of the final prognosis. We can therefore say that the dose to the skin can be considered as potentially lethal whenever lesions cover more than 30% of the total body area. Thus non-lethal disabling effects could appear in the case of severe irradiation of the skin over a surface area covering less than 30% of the total body area. High doses to the skin over a large surface area can be caused by extensive skin contamination by beta and alpha emitters.

The NRPB has no models for this type of effect. However, it can be observed clinically and therefore the maximum risk level for deterministic effects is attributed to it.

2.2.6. Severe mental retardation in the foetus

For the brain, the critical period is between the eighth week and the beginning of the sixteenth week, since the death of the neurones, or their failure to migrate, could result in mental retardation. During this period, the threshold is estimated at 0.12 Gy. The literature shows that during this period, there is a linear correlation between mental retardation and dose, with a loss of 30 IQ points per gray (ICRP Publication 60). The risk subsists, to a lesser extent, up to the 25th week. Despite the fact that very little information is available on this type of effect during this period, the threshold can be estimated at 0.24 Gy.

Severely mentally retarded children grow up incapable of carrying out simple arithmetic and cannot be self-sufficient. The large majority of these children are incapable of integrating the normal education system and have IQs of less than 70, compared to the national average of 100.

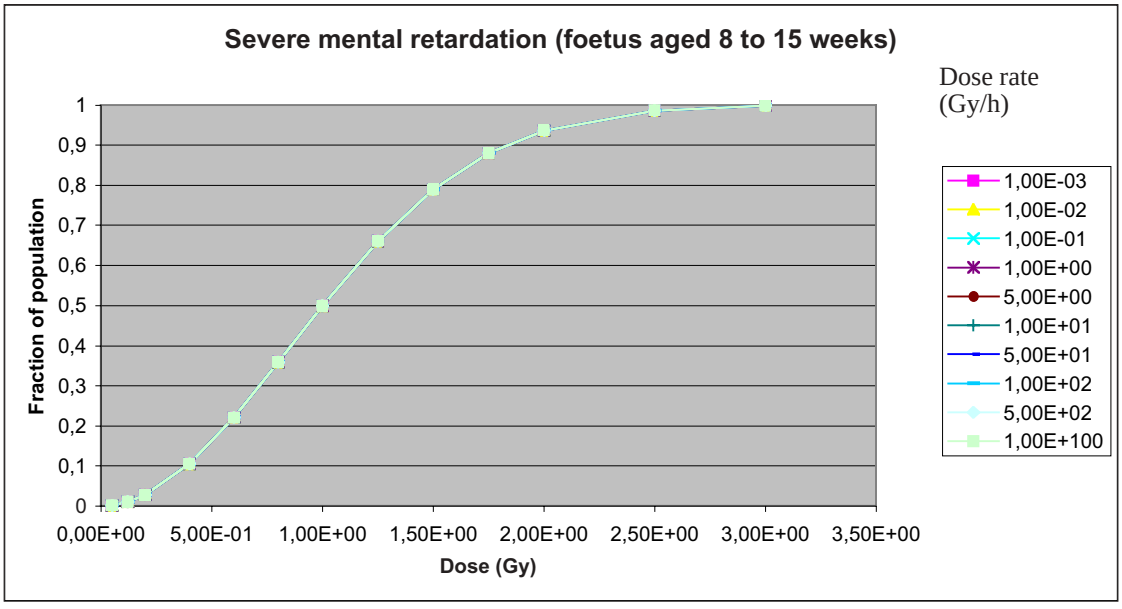
Before the eighth week and after the 25th week, the effects on mental development are negligible.

Severe mental retardation in the fœtus (8 to 15 weeks)

θ_8	θ_1	ν	RBE	D_1
Gy	Gy^2/h		(alpha)	Gy
1	0	2	-	0.12

Dose (Gy) / Dose rate (Gy/h)	5,00E-02	1,20E-01	2,00E-01	4,00E-01	6,00E-01	8,00E-01	1,00E+00	1,25E+00	1,50E+00	1,75E+00	2,00E+00	2,50E+00	3,00E+00
1,00E-03	1,73E-03	9,93E-03	2,73E-02	1,05E-01	2,21E-01	3,58E-01	5,00E-01	6,61E-01	7,90E-01	8,80E-01	9,38E-01	9,87E-01	9,98E-01
1,00E-02	1,73E-03	9,93E-03	2,73E-02	1,05E-01	2,21E-01	3,58E-01	5,00E-01	6,61E-01	7,90E-01	8,80E-01	9,38E-01	9,87E-01	9,98E-01
1,00E-01	1,73E-03	9,93E-03	2,73E-02	1,05E-01	2,21E-01	3,58E-01	5,00E-01	6,61E-01	7,90E-01	8,80E-01	9,38E-01	9,87E-01	9,98E-01
1,00E+00	1,73E-03	9,93E-03	2,73E-02	1,05E-01	2,21E-01	3,58E-01	5,00E-01	6,61E-01	7,90E-01	8,80E-01	9,38E-01	9,87E-01	9,98E-01
5,00E+00	1,73E-03	9,93E-03	2,73E-02	1,05E-01	2,21E-01	3,58E-01	5,00E-01	6,61E-01	7,90E-01	8,80E-01	9,38E-01	9,87E-01	9,98E-01
1,00E+01	1,73E-03	9,93E-03	2,73E-02	1,05E-01	2,21E-01	3,58E-01	5,00E-01	6,61E-01	7,90E-01	8,80E-01	9,38E-01	9,87E-01	9,98E-01
5,00E+01	1,73E-03	9,93E-03	2,73E-02	1,05E-01	2,21E-01	3,58E-01	5,00E-01	6,61E-01	7,90E-01	8,80E-01	9,38E-01	9,87E-01	9,98E-01
1,00E+02	1,73E-03	9,93E-03	2,73E-02	1,05E-01	2,21E-01	3,58E-01	5,00E-01	6,61E-01	7,90E-01	8,80E-01	9,38E-01	9,87E-01	9,98E-01
5,00E+02	1,73E-03	9,93E-03	2,73E-02	1,05E-01	2,21E-01	3,58E-01	5,00E-01	6,61E-01	7,90E-01	8,80E-01	9,38E-01	9,87E-01	9,98E-01
1,00E+100	1,73E-03	9,93E-03	2,73E-02	1,05E-01	2,21E-01	3,58E-01	5,00E-01	6,61E-01	7,90E-01	8,80E-01	9,38E-01	9,87E-01	9,98E-01

>D1
>D5
>D50

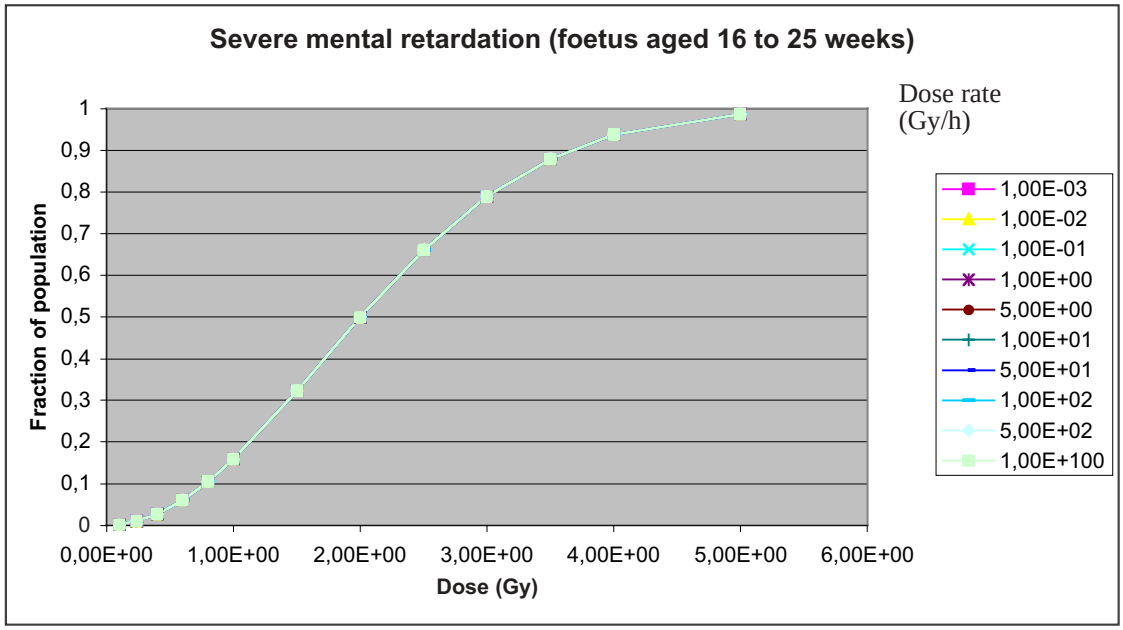


Severe mental retardation in the fœtus (16 to 25 weeks)

θ_8 Gy	θ_1 Gy^2/h	ν	RBE (alpha)	D_1 Gy
2	0	2	-	0.24

Dose (Gy) / Dose rate (Gy/h)	1,00E-01	2,40E-01	4,00E-01	6,00E-01	8,00E-01	1,00E+00	1,50E+00	2,00E+00	2,50E+00	3,00E+00	3,50E+00	4,00E+00	5,00E+00
1,00E-03	1,73E-03	9,93E-03	2,73E-02	6,05E-02	1,05E-01	1,59E-01	3,23E-01	5,00E-01	6,61E-01	7,90E-01	8,80E-01	9,38E-01	9,87E-01
1,00E-02	1,73E-03	9,93E-03	2,73E-02	6,05E-02	1,05E-01	1,59E-01	3,23E-01	5,00E-01	6,61E-01	7,90E-01	8,80E-01	9,38E-01	9,87E-01
1,00E-01	1,73E-03	9,93E-03	2,73E-02	6,05E-02	1,05E-01	1,59E-01	3,23E-01	5,00E-01	6,61E-01	7,90E-01	8,80E-01	9,38E-01	9,87E-01
1,00E+00	1,73E-03	9,93E-03	2,73E-02	6,05E-02	1,05E-01	1,59E-01	3,23E-01	5,00E-01	6,61E-01	7,90E-01	8,80E-01	9,38E-01	9,87E-01
5,00E+00	1,73E-03	9,93E-03	2,73E-02	6,05E-02	1,05E-01	1,59E-01	3,23E-01	5,00E-01	6,61E-01	7,90E-01	8,80E-01	9,38E-01	9,87E-01
1,00E+01	1,73E-03	9,93E-03	2,73E-02	6,05E-02	1,05E-01	1,59E-01	3,23E-01	5,00E-01	6,61E-01	7,90E-01	8,80E-01	9,38E-01	9,87E-01
5,00E+01	1,73E-03	9,93E-03	2,73E-02	6,05E-02	1,05E-01	1,59E-01	3,23E-01	5,00E-01	6,61E-01	7,90E-01	8,80E-01	9,38E-01	9,87E-01
1,00E+02	1,73E-03	9,93E-03	2,73E-02	6,05E-02	1,05E-01	1,59E-01	3,23E-01	5,00E-01	6,61E-01	7,90E-01	8,80E-01	9,38E-01	9,87E-01
5,00E+02	1,73E-03	9,93E-03	2,73E-02	6,05E-02	1,05E-01	1,59E-01	3,23E-01	5,00E-01	6,61E-01	7,90E-01	8,80E-01	9,38E-01	9,87E-01
1,00E+100	1,73E-03	9,93E-03	2,73E-02	6,05E-02	1,05E-01	1,59E-01	3,23E-01	5,00E-01	6,61E-01	7,90E-01	8,80E-01	9,38E-01	9,87E-01

>D1
>D5
>D50



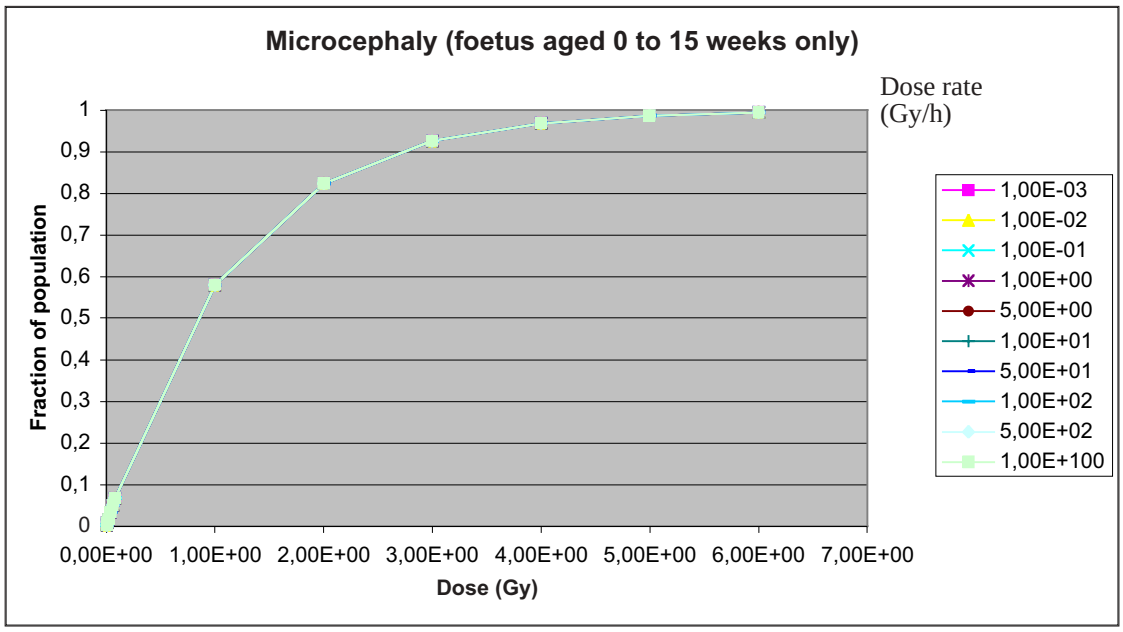
2.2.7. Microcephaly

Cases of microcephalus have been observed in exposed pregnant women, notably in survivors of the atomic blasts at Hiroshima and Nagasaki[5]. The risk is highest between the first and fifteenth weeks. Even if the risk persists, it decreases rapidly after the fifteenth week. The NRPB recommends a threshold dose of 0.05 Gy in line with previous studies[6].

θ_8 Gy	θ_1 Gy^2/h	ν	RBE (alpha)	D_1 Gy
0.8	0	1	-	0.05

Dose (Gy) / Dose rate (Gy/h)	2,50E-03	5,00E-03	1,00E-02	2,00E-02	4,00E-02	6,00E-02	8,00E-02	1,00E+00	2,00E+00	3,00E+00	4,00E+00	5,00E+00	6,00E+00
1,00E-03	2,16E-03	4,32E-03	8,63E-03	1,72E-02	3,41E-02	5,07E-02	6,70E-02	5,80E-01	8,23E-01	9,26E-01	9,69E-01	9,87E-01	9,94E-01
1,00E-02	2,16E-03	4,32E-03	8,63E-03	1,72E-02	3,41E-02	5,07E-02	6,70E-02	5,80E-01	8,23E-01	9,26E-01	9,69E-01	9,87E-01	9,94E-01
1,00E-01	2,16E-03	4,32E-03	8,63E-03	1,72E-02	3,41E-02	5,07E-02	6,70E-02	5,80E-01	8,23E-01	9,26E-01	9,69E-01	9,87E-01	9,94E-01
1,00E+00	2,16E-03	4,32E-03	8,63E-03	1,72E-02	3,41E-02	5,07E-02	6,70E-02	5,80E-01	8,23E-01	9,26E-01	9,69E-01	9,87E-01	9,94E-01
5,00E+00	2,16E-03	4,32E-03	8,63E-03	1,72E-02	3,41E-02	5,07E-02	6,70E-02	5,80E-01	8,23E-01	9,26E-01	9,69E-01	9,87E-01	9,94E-01
1,00E+01	2,16E-03	4,32E-03	8,63E-03	1,72E-02	3,41E-02	5,07E-02	6,70E-02	5,80E-01	8,23E-01	9,26E-01	9,69E-01	9,87E-01	9,94E-01
5,00E+01	2,16E-03	4,32E-03	8,63E-03	1,72E-02	3,41E-02	5,07E-02	6,70E-02	5,80E-01	8,23E-01	9,26E-01	9,69E-01	9,87E-01	9,94E-01
1,00E+02	2,16E-03	4,32E-03	8,63E-03	1,72E-02	3,41E-02	5,07E-02	6,70E-02	5,80E-01	8,23E-01	9,26E-01	9,69E-01	9,87E-01	9,94E-01
5,00E+02	2,16E-03	4,32E-03	8,63E-03	1,72E-02	3,41E-02	5,07E-02	6,70E-02	5,80E-01	8,23E-01	9,26E-01	9,69E-01	9,87E-01	9,94E-01
1,00E+100	2,16E-03	4,32E-03	8,63E-03	1,72E-02	3,41E-02	5,07E-02	6,70E-02	5,80E-01	8,23E-01	9,26E-01	9,69E-01	9,87E-01	9,94E-01

>D1
>D5
>D50



5 Ishimaru J., Nakashima E., Kawamoto S., Relationship of height, body weight, head circumference at age 18 to gamma and neutron doses among *in utero* exposed children in Hiroshima and Nagasaki. Hiroshima, Radiation Effects Research Foundation, TR19-84 (1984).

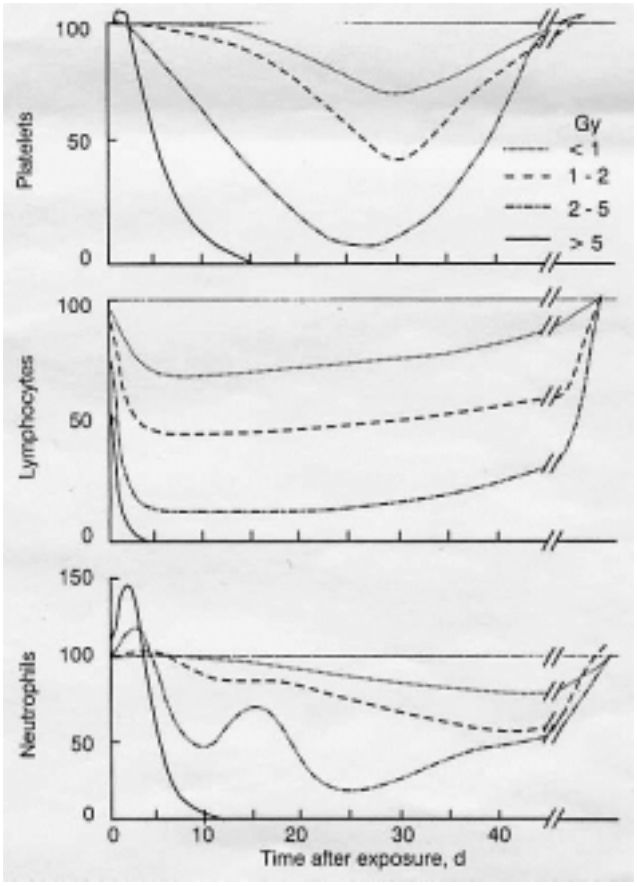
6 Scott, BR and Hahn, F F. Early occurring and continuing effects. In Health effects models for nuclear power plant accident consequence analysis. Low LET radiation. Washington DC, Nuclear Regulatory Commission. NUREG/CR-4214 (SAND85-7185), Rev. 1, Part II (1989).

2.3. Lethal effects

2.3.1. Haematopoietic syndrome

Blood cells are produced in the haematopoietic tissue located in the bone marrow. A dose of more than 2 Gy to the bone marrow results in a high risk of death. Many blood stem cells are destroyed at this dose. Death occurs between 20 and 60 days after irradiation due to haemorrhaging caused by the drop in the number of platelets, resulting in poor coagulation, but also due to infection since the defence system is weakened.

Lymphocytes give a good indication of the state of the bone marrow. Neutrophils and platelets also give an indication of damage to the haematopoietic tissue.



The preceding graphs show the changes occurring in the various cell lines of the haematopoietic tissue after irradiation of the bone marrow at doses of between 0 and more than 5 Gy.

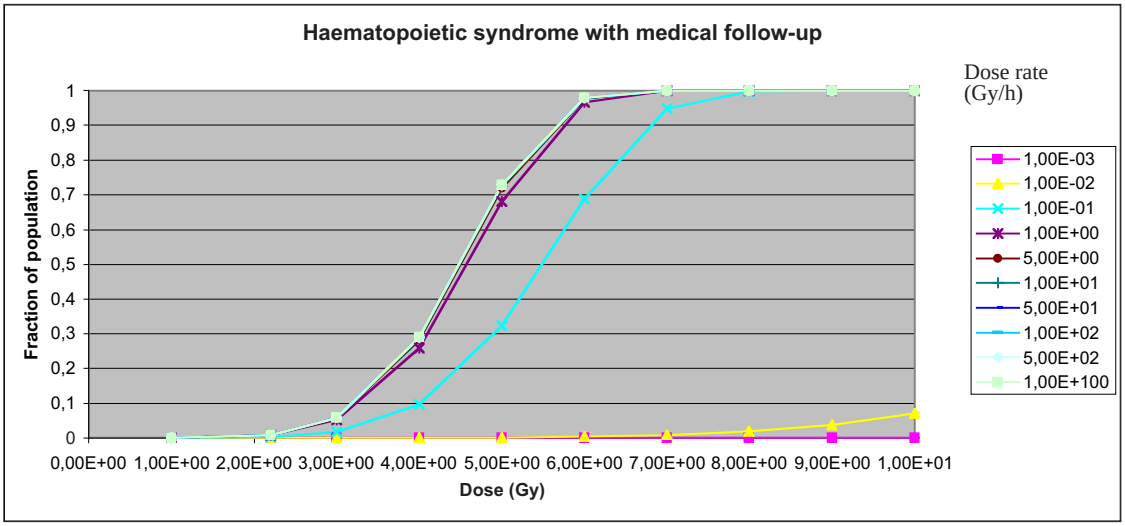
Risk of haematopoietic syndrome

(with medical follow-up after exposure)

θ_8 Gy	θ_1 Gy^2/h	ν	RBE (neutrons)	RBE (alpha)	D_1 Gy
4.5	0.1	6	1.5	2	2.2

Dose (Gy) / Dose rate (Gy/h)	1,00E+00	2,20E+00	3,00E+00	4,00E+00	5,00E+00	6,00E+00	7,00E+00	8,00E+00	9,00E+00	1,00E+01	1,10E+01	1,20E+01	1,30E+01
1,00E-03	5,32E-13	6,03E-11	3,88E-10	2,18E-09	8,32E-09	2,48E-08	6,26E-08	1,40E-07	2,83E-07	5,32E-07	9,43E-07	1,59E-06	2,57E-06
1,00E-02	7,46E-08	8,46E-06	5,44E-05	3,05E-04	1,16E-03	3,47E-03	8,74E-03	1,94E-02	3,89E-02	7,19E-02	1,24E-01	2,00E-01	3,02E-01
1,00E-01	2,50E-05	2,84E-03	1,81E-02	9,75E-02	3,24E-01	6,89E-01	9,47E-01	9,99E-01	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00
1,00E+00	7,32E-05	8,26E-03	5,19E-02	2,59E-01	6,81E-01	9,67E-01	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00
5,00E+00	8,13E-05	9,17E-03	5,75E-02	2,83E-01	7,19E-01	9,77E-01	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00
1,00E+01	8,24E-05	9,30E-03	5,83E-02	2,86E-01	7,24E-01	9,79E-01	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00
5,00E+01	8,32E-05	9,39E-03	5,89E-02	2,89E-01	7,28E-01	9,79E-01	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00
1,00E+02	8,34E-05	9,41E-03	5,90E-02	2,89E-01	7,28E-01	9,80E-01	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00
5,00E+02	8,34E-05	9,42E-03	5,90E-02	2,90E-01	7,29E-01	9,80E-01	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00
1,00E+100	8,35E-05	9,42E-03	5,90E-02	2,90E-01	7,29E-01	9,80E-01	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00

>D50
>D5
>D1

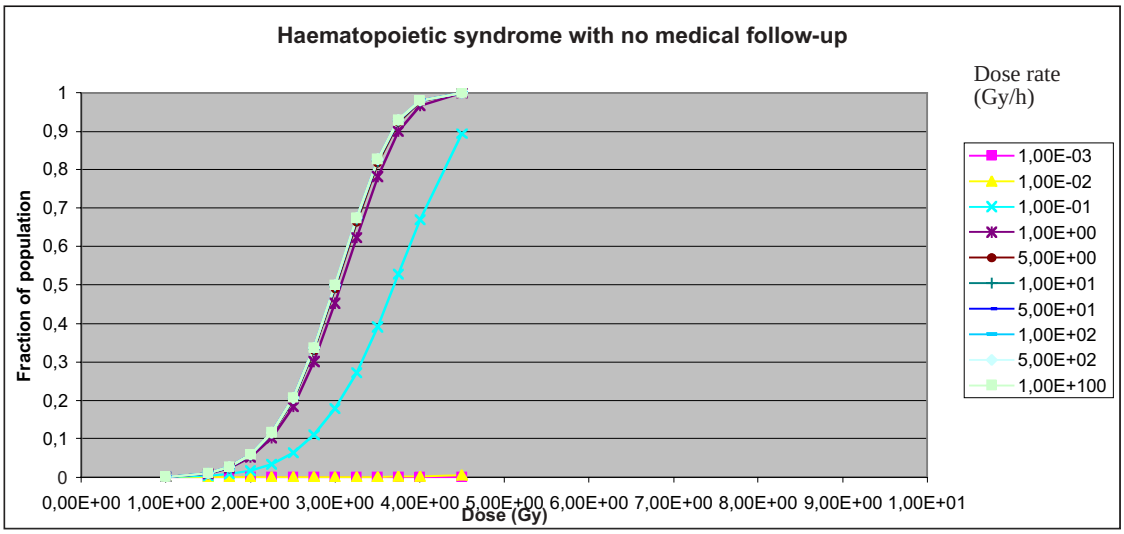


Risk of haematopoietic syndrome
(with no medical follow-up after exposure)

θ_8 Gy	θ_1 Gy^2/h	ν	RBE (neutrons)	RBE (alpha)	D_1 Gy
3	0.07	6	1.5	2	1.5

Dose (Gy) / Dose rate (Gy/h)	1,00E+00	1,50E+00	1,75E+00	2,00E+00	2,25E+00	2,50E+00	2,75E+00	3,00E+00	3,25E+00	3,50E+00	3,75E+00	4,00E+00	4,50E+00
1,00E-03	4,58E-12	5,22E-11	1,32E-10	2,93E-10	5,94E-10	1,12E-09	1,98E-09	3,34E-09	5,40E-09	8,42E-09	1,27E-08	1,88E-08	3,80E-08
1,00E-02	6,93E-07	7,90E-06	1,99E-05	4,44E-05	8,99E-05	1,69E-04	3,00E-04	5,05E-04	8,16E-04	1,27E-03	1,93E-03	2,84E-03	5,74E-03
1,00E-01	2,70E-04	3,07E-03	7,73E-03	1,71E-02	3,44E-02	6,38E-02	1,10E-01	1,79E-01	2,73E-01	3,91E-01	5,28E-01	6,69E-01	8,94E-01
1,00E+00	8,28E-04	9,39E-03	2,35E-02	5,16E-02	1,02E-01	1,83E-01	3,01E-01	4,53E-01	6,23E-01	7,82E-01	9,00E-01	9,66E-01	9,99E-01
5,00E+00	9,24E-04	1,05E-02	2,62E-02	5,75E-02	1,13E-01	2,02E-01	3,30E-01	4,90E-01	6,64E-01	8,17E-01	9,24E-01	9,77E-01	1,00E+00
1,00E+01	9,37E-04	1,06E-02	2,66E-02	5,82E-02	1,15E-01	2,05E-01	3,33E-01	4,95E-01	6,69E-01	8,22E-01	9,26E-01	9,79E-01	1,00E+00
5,00E+01	9,48E-04	1,07E-02	2,69E-02	5,89E-02	1,16E-01	2,07E-01	3,36E-01	4,99E-01	6,73E-01	8,25E-01	9,28E-01	9,79E-01	1,00E+00
1,00E+02	9,49E-04	1,08E-02	2,69E-02	5,90E-02	1,16E-01	2,07E-01	3,37E-01	5,00E-01	6,73E-01	8,25E-01	9,29E-01	9,80E-01	1,00E+00
5,00E+02	9,50E-04	1,08E-02	2,69E-02	5,90E-02	1,16E-01	2,07E-01	3,37E-01	5,00E-01	6,74E-01	8,26E-01	9,29E-01	9,80E-01	1,00E+00
1,00E+100	9,50E-04	1,08E-02	2,69E-02	5,90E-02	1,16E-01	2,07E-01	3,37E-01	5,00E-01	6,74E-01	8,26E-01	9,29E-01	9,80E-01	1,00E+00

>D50
>D5
>D1



2.3.2. Gastro-intestinal syndrome

This effect occurs after the prodromal phase, the symptoms of which are described above (see Section 2.1.1). In addition to the symptoms encountered during the prodromal phase, gastro-intestinal syndrome also results in weight loss, a decrease in intestinal absorption, sometimes accompanied by digestive haemorrhage, and bacterial proliferation that can cause death. Generally speaking, the dose required for gastro-intestinal syndrome to occur is higher than that required for haematopoietic syndrome (see Section 2.3.1). When whole-body irradiation occurs at this dose, the person will die from the damage to the bone marrow.

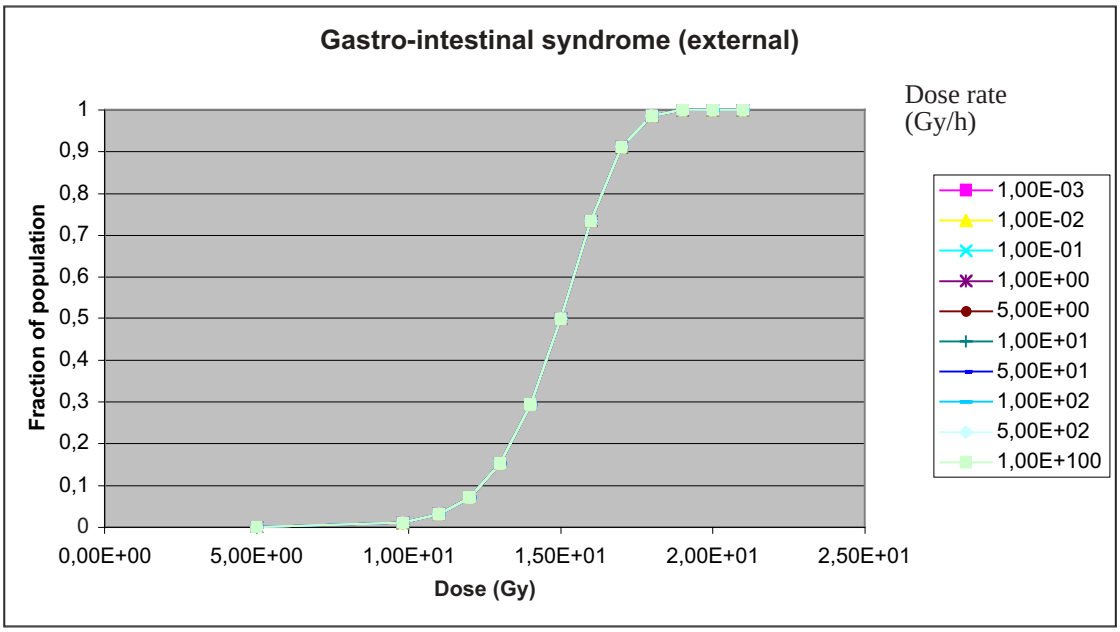
Risk of gastro-intestinal syndrome in the case of external irradiation

Irradiated organ: small intestine

θ_8 Gy	θ_1 Gy^2/h	θ	RBE (alpha)	D_1 Gy
15	0	10	-	9.8

Dose (Gy) / Dose rate (Gy/h)	5,00E+00	9,80E+00	1,10E+01	1,20E+01	1,30E+01	1,40E+01	1,50E+01	1,60E+01	1,70E+01	1,80E+01	1,90E+01	2,00E+01	2,10E+01
1,00E-03	1,17E-05	9,77E-03	3,07E-02	7,17E-02	1,53E-01	2,94E-01	5,00E-01	7,33E-01	9,11E-01	9,86E-01	9,99E-01	1,00E+00	1,00E+00
1,00E-02	1,17E-05	9,77E-03	3,07E-02	7,17E-02	1,53E-01	2,94E-01	5,00E-01	7,33E-01	9,11E-01	9,86E-01	9,99E-01	1,00E+00	1,00E+00
1,00E-01	1,17E-05	9,77E-03	3,07E-02	7,17E-02	1,53E-01	2,94E-01	5,00E-01	7,33E-01	9,11E-01	9,86E-01	9,99E-01	1,00E+00	1,00E+00
1,00E+00	1,17E-05	9,77E-03	3,07E-02	7,17E-02	1,53E-01	2,94E-01	5,00E-01	7,33E-01	9,11E-01	9,86E-01	9,99E-01	1,00E+00	1,00E+00
5,00E+00	1,17E-05	9,77E-03	3,07E-02	7,17E-02	1,53E-01	2,94E-01	5,00E-01	7,33E-01	9,11E-01	9,86E-01	9,99E-01	1,00E+00	1,00E+00
1,00E+01	1,17E-05	9,77E-03	3,07E-02	7,17E-02	1,53E-01	2,94E-01	5,00E-01	7,33E-01	9,11E-01	9,86E-01	9,99E-01	1,00E+00	1,00E+00
5,00E+01	1,17E-05	9,77E-03	3,07E-02	7,17E-02	1,53E-01	2,94E-01	5,00E-01	7,33E-01	9,11E-01	9,86E-01	9,99E-01	1,00E+00	1,00E+00
1,00E+02	1,17E-05	9,77E-03	3,07E-02	7,17E-02	1,53E-01	2,94E-01	5,00E-01	7,33E-01	9,11E-01	9,86E-01	9,99E-01	1,00E+00	1,00E+00
5,00E+02	1,17E-05	9,77E-03	3,07E-02	7,17E-02	1,53E-01	2,94E-01	5,00E-01	7,33E-01	9,11E-01	9,86E-01	9,99E-01	1,00E+00	1,00E+00
1,00E+100	1,17E-05	9,77E-03	3,07E-02	7,17E-02	1,53E-01	2,94E-01	5,00E-01	7,33E-01	9,11E-01	9,86E-01	9,99E-01	1,00E+00	1,00E+00

>D50
>D5
>D1



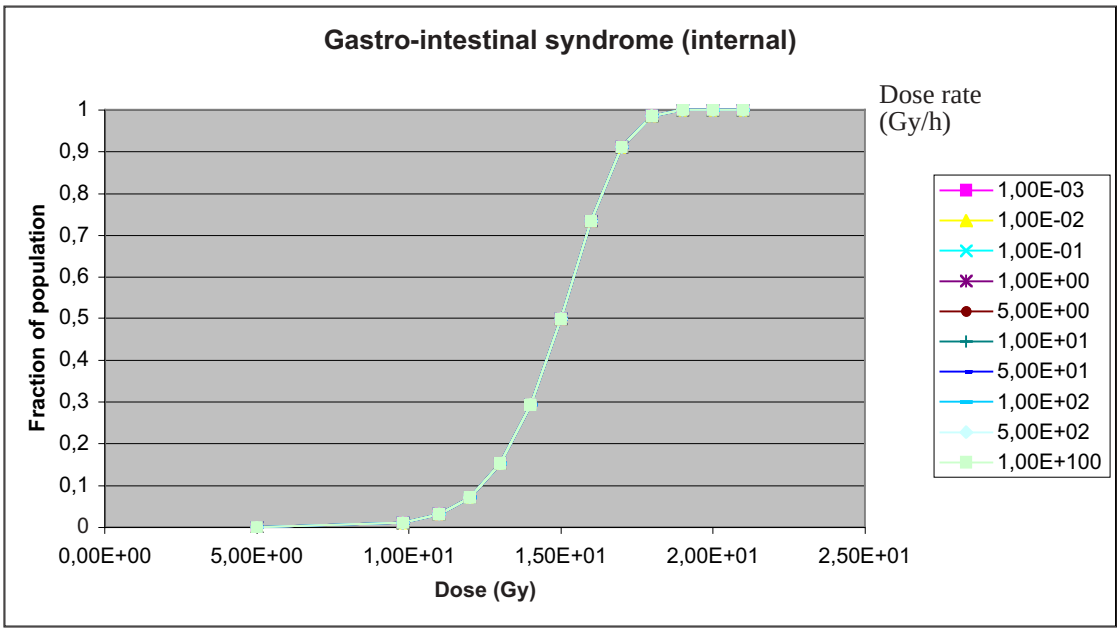
Risk of gastro-intestinal syndrome in the case of internal irradiation

Irradiated organ: colon

θ_8 Gy	θ_1 Gy^2/h	ν	RBE (alpha)	D_1 Gy
15	0	10	-	9.8

Dose (Gy) / Dose rate (Gy/h)	5,00E+00	9,80E+00	1,10E+01	1,20E+01	1,30E+01	1,40E+01	1,50E+01	1,60E+01	1,70E+01	1,80E+01	1,90E+01	2,00E+01	2,10E+01
1,00E-03	1,17E-05	9,77E-03	3,07E-02	7,17E-02	1,53E-01	2,94E-01	5,00E-01	7,33E-01	9,11E-01	9,86E-01	9,99E-01	1,00E+00	1,00E+00
1,00E-02	1,17E-05	9,77E-03	3,07E-02	7,17E-02	1,53E-01	2,94E-01	5,00E-01	7,33E-01	9,11E-01	9,86E-01	9,99E-01	1,00E+00	1,00E+00
1,00E-01	1,17E-05	9,77E-03	3,07E-02	7,17E-02	1,53E-01	2,94E-01	5,00E-01	7,33E-01	9,11E-01	9,86E-01	9,99E-01	1,00E+00	1,00E+00
1,00E+00	1,17E-05	9,77E-03	3,07E-02	7,17E-02	1,53E-01	2,94E-01	5,00E-01	7,33E-01	9,11E-01	9,86E-01	9,99E-01	1,00E+00	1,00E+00
5,00E+00	1,17E-05	9,77E-03	3,07E-02	7,17E-02	1,53E-01	2,94E-01	5,00E-01	7,33E-01	9,11E-01	9,86E-01	9,99E-01	1,00E+00	1,00E+00
1,00E+01	1,17E-05	9,77E-03	3,07E-02	7,17E-02	1,53E-01	2,94E-01	5,00E-01	7,33E-01	9,11E-01	9,86E-01	9,99E-01	1,00E+00	1,00E+00
5,00E+01	1,17E-05	9,77E-03	3,07E-02	7,17E-02	1,53E-01	2,94E-01	5,00E-01	7,33E-01	9,11E-01	9,86E-01	9,99E-01	1,00E+00	1,00E+00
1,00E+02	1,17E-05	9,77E-03	3,07E-02	7,17E-02	1,53E-01	2,94E-01	5,00E-01	7,33E-01	9,11E-01	9,86E-01	9,99E-01	1,00E+00	1,00E+00
5,00E+02	1,17E-05	9,77E-03	3,07E-02	7,17E-02	1,53E-01	2,94E-01	5,00E-01	7,33E-01	9,11E-01	9,86E-01	9,99E-01	1,00E+00	1,00E+00
1,00E+100	1,17E-05	9,77E-03	3,07E-02	7,17E-02	1,53E-01	2,94E-01	5,00E-01	7,33E-01	9,11E-01	9,86E-01	9,99E-01	1,00E+00	1,00E+00

>D50
>D5
>D1



2.3.3. Pulmonary syndrome

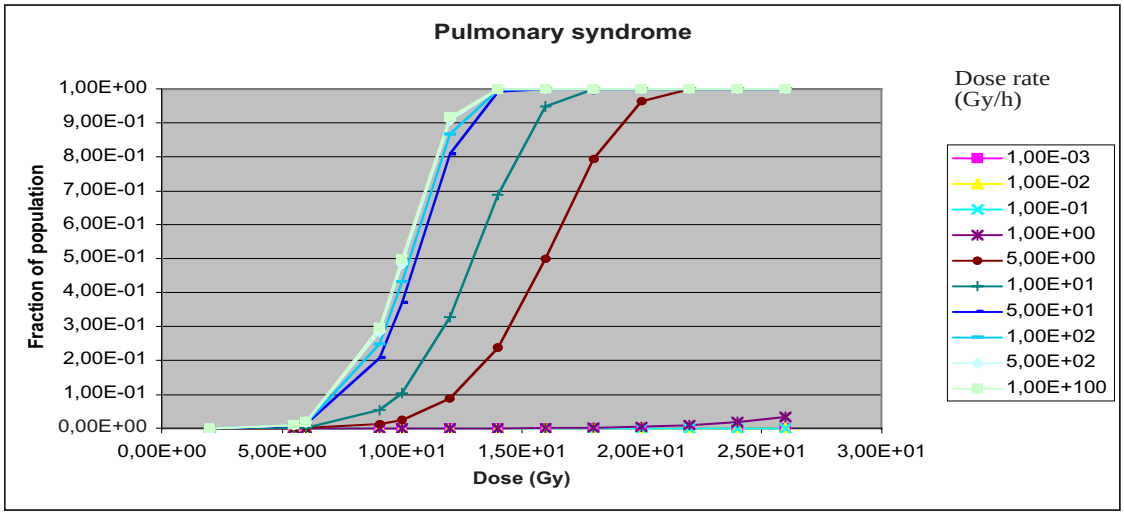
The lungs are relatively sensitive and the damage caused by irradiation develops in two stages. During the first stage (a few weeks after exposure), pneumonia and oedema are observed. In the long term, pulmonary fibrosis develops and alveoli are lost and replaced by collagen. This phenomenon makes the pulmonary parenchyma less elastic. The symptoms are respiratory distress, fever and a dry cough. At high doses, these functional and structural modifications can cause death. Lung response is highly dependent on dose and dose rate.

The lungs can be irradiated by external exposure or internal contamination by the inhalation of one or more radioactive isotopes. The risk is greater when alpha and beta emitters are inhaled. The dose/frequency curve is modified by applying a biological effectiveness factor of 7.

θ_8 Gy	θ_1 Gy^2/h	ν	RBE (alpha)	D_1 Gy
10	30	7	7	5.5

Dose (Gy) / Dose rate (Gy/h)	2,00E+00	5,50E+00	6,00E+00	9,07E+00	1,00E+01	1,20E+01	1,40E+01	1,60E+01	1,80E+01	2,00E+01	2,20E+01	2,40E+01	2,60E+01
1,00E-03	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
1,00E-02	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,11E-16	2,22E-16	4,44E-16	7,77E-16	1,44E-15	2,44E-15
1,00E-01	3,33E-16	3,84E-13	7,05E-13	1,27E-11	2,52E-11	9,03E-11	2,66E-10	6,76E-10	1,54E-09	3,22E-09	6,28E-09	1,16E-08	2,02E-08
1,00E+00	5,42E-10	6,44E-07	1,18E-06	2,14E-05	4,23E-05	1,52E-04	4,46E-04	1,14E-03	2,59E-03	5,40E-03	1,05E-02	1,92E-02	3,34E-02
5,00E+00	3,31E-07	3,93E-04	7,23E-04	1,30E-02	2,55E-02	8,84E-02	2,38E-01	5,00E-01	7,94E-01	9,63E-01	9,98E-01	1,00E+00	1,00E+00
1,00E+01	1,41E-06	1,68E-03	3,09E-03	5,43E-02	1,05E-01	3,27E-01	6,88E-01	9,48E-01	9,99E-01	1,00E+00	1,00E+00	1,00E+00	1,00E+00
5,00E+01	5,90E-06	6,99E-03	1,28E-02	2,08E-01	3,69E-01	8,08E-01	9,92E-01	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00
1,00E+02	7,21E-06	8,54E-03	1,57E-02	2,48E-01	4,31E-01	8,67E-01	9,97E-01	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00
5,00E+02	8,51E-06	1,01E-02	1,84E-02	2,85E-01	4,86E-01	9,08E-01	9,99E-01	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00
1,00E+100	8,87E-06	1,05E-02	1,92E-02	2,95E-01	5,00E-01	9,17E-01	9,99E-01	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00

>D50
>D5
>D1



2.3.4. Embryonic and fœtal mortality

In the very early stages of pregnancy (up to the 18th day after conception), the effects of ionising radiation may, depending on the dose, result in the death of the egg, which goes unnoticed most of the time, or have no effect on the development of the embryo. At this stage, the cells have no specific functions. Those that are destroyed are replaced by others with the same potential.

At the later stages of differentiation (19 to 150 days), the surviving cells can no longer change their functions and the number of cells destined to form each of the organs is limited. The risk decreases after the 150th day.

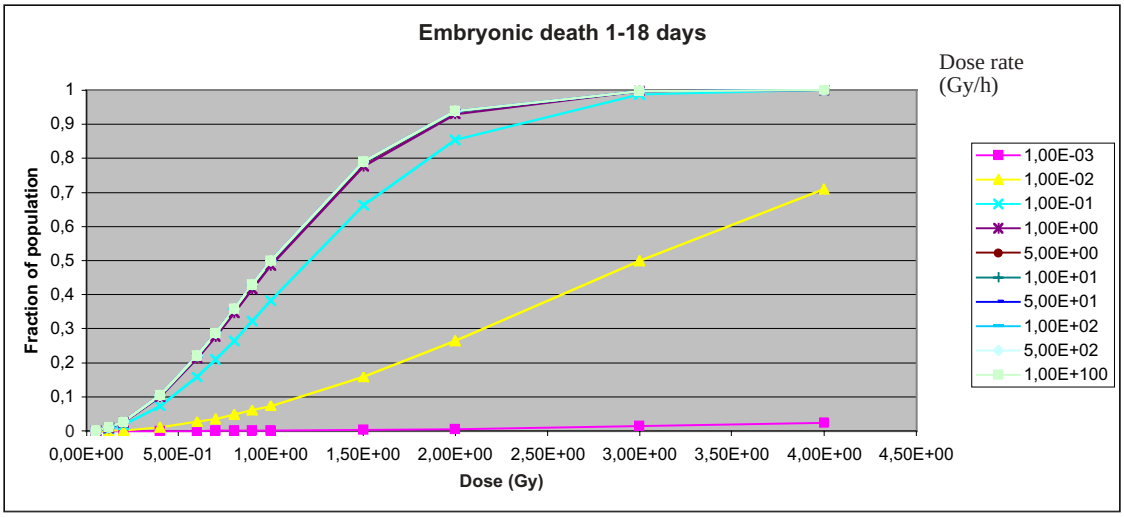
Studies suggest a threshold of 0.12 Gy for the period stretching from the 1st to the 18th day after conception, 0.37 Gy if irradiation occurs between the 18^{th} and 150^{th} days and finally, 1.5 Gy for the remainder of the pregnancy.

Death of the embryo (1 to 18 days)

θ_8 Gy	θ_1 Gy^2/h	θ	RBE (alpha)	D_1 Gy
1	0.02	2	2	0.12

Dose (Gy) / Dose rate (Gy/h)	5,00E-02	1,20E-01	2,00E-01	4,00E-01	6,00E-01	7,00E-01	8,00E-01	9,00E-01	1,00E+00	1,50E+00	2,00E+00	3,00E+00	4,00E+00
1,00E-03	3,93E-06	2,26E-05	6,29E-05	2,51E-04	5,66E-04	7,70E-04	1,01E-03	1,27E-03	1,57E-03	3,53E-03	6,27E-03	1,40E-02	2,48E-02
1,00E-02	1,93E-04	1,11E-03	3,08E-03	1,22E-02	2,73E-02	3,70E-02	4,81E-02	6,05E-02	7,41E-02	1,59E-01	2,65E-01	5,00E-01	7,08E-01
1,00E-01	1,20E-03	6,91E-03	1,91E-02	7,41E-02	1,59E-01	2,10E-01	2,65E-01	3,23E-01	3,82E-01	6,61E-01	8,54E-01	9,87E-01	1,00E+00
1,00E+00	1,66E-03	9,55E-03	2,63E-02	1,01E-01	2,13E-01	2,79E-01	3,47E-01	4,17E-01	4,86E-01	7,77E-01	9,30E-01	9,98E-01	1,00E+00
5,00E+00	1,72E-03	9,85E-03	2,71E-02	1,04E-01	2,19E-01	2,86E-01	3,56E-01	4,27E-01	4,97E-01	7,87E-01	9,36E-01	9,98E-01	1,00E+00
1,00E+01	1,72E-03	9,89E-03	2,72E-02	1,05E-01	2,20E-01	2,87E-01	3,57E-01	4,28E-01	4,99E-01	7,88E-01	9,37E-01	9,98E-01	1,00E+00
5,00E+01	1,73E-03	9,92E-03	2,73E-02	1,05E-01	2,21E-01	2,88E-01	3,58E-01	4,29E-01	5,00E-01	7,90E-01	9,37E-01	9,98E-01	1,00E+00
1,00E+02	1,73E-03	9,93E-03	2,73E-02	1,05E-01	2,21E-01	2,88E-01	3,58E-01	4,29E-01	5,00E-01	7,90E-01	9,37E-01	9,98E-01	1,00E+00
5,00E+02	1,73E-03	9,93E-03	2,73E-02	1,05E-01	2,21E-01	2,88E-01	3,58E-01	4,30E-01	5,00E-01	7,90E-01	9,37E-01	9,98E-01	1,00E+00
1,00E+100	1,73E-03	9,93E-03	2,73E-02	1,05E-01	2,21E-01	2,88E-01	3,58E-01	4,30E-01	5,00E-01	7,90E-01	9,38E-01	9,98E-01	1,00E+00

>D50
>D5
>D1

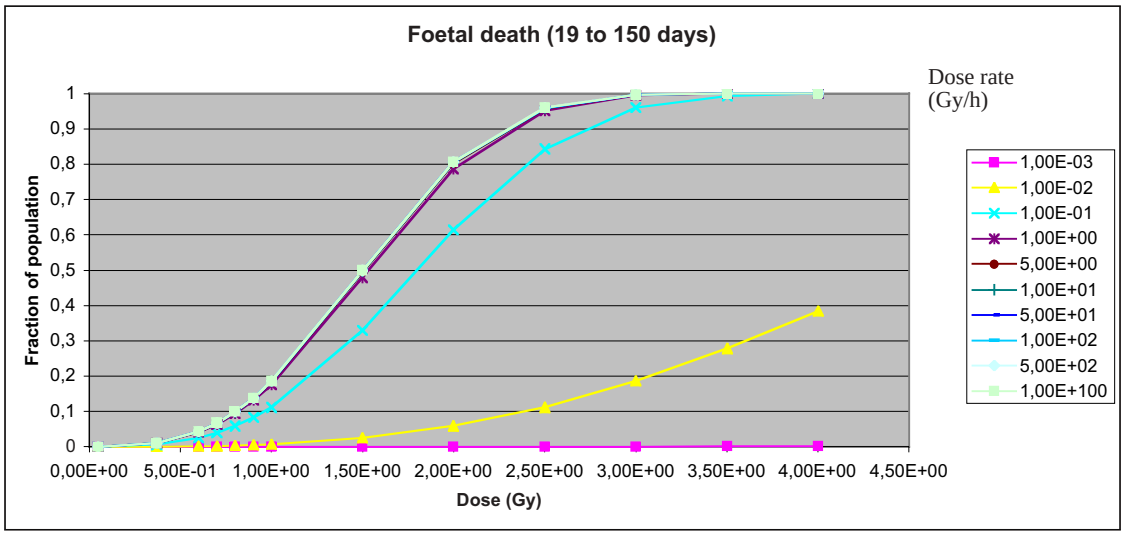


Death of the foetus (19 to 150 days)

θ_8 Gy	θ_1 Gy^2/h	ν	RBE (alpha)	D_1 Gy
1.5	0.03	3	2	0.37

Dose (Gy) / Dose rate (Gy/h)	5,00E-02	3,70E-01	6,00E-01	7,00E-01	8,00E-01	9,00E-01	1,00E+00	1,50E+00	2,00E+00	2,50E+00	3,00E+00	3,50E+00	4,00E+00
1,00E-03	2,77E-09	1,12E-06	4,79E-06	7,61E-06	1,14E-05	1,62E-05	2,22E-05	7,48E-05	1,77E-04	3,46E-04	5,99E-04	9,50E-04	1,42E-03
1,00E-02	9,51E-07	3,85E-04	1,64E-03	2,61E-03	3,89E-03	5,53E-03	7,58E-03	2,53E-02	5,90E-02	1,12E-01	1,86E-01	2,78E-01	3,85E-01
1,00E-01	1,49E-05	6,00E-03	2,53E-02	3,99E-02	5,90E-02	8,30E-02	1,12E-01	3,30E-01	6,14E-01	8,44E-01	9,60E-01	9,94E-01	1,00E+00
1,00E+00	2,42E-05	9,76E-03	4,09E-02	6,42E-02	9,43E-02	1,32E-01	1,76E-01	4,80E-01	7,87E-01	9,51E-01	9,95E-01	1,00E+00	1,00E+00
5,00E+00	2,54E-05	1,02E-02	4,29E-02	6,72E-02	9,87E-02	1,38E-01	1,84E-01	4,96E-01	8,03E-01	9,58E-01	9,96E-01	1,00E+00	1,00E+00
1,00E+01	2,55E-05	1,03E-02	4,31E-02	6,76E-02	9,92E-02	1,38E-01	1,85E-01	4,98E-01	8,05E-01	9,59E-01	9,96E-01	1,00E+00	1,00E+00
5,00E+01	2,56E-05	1,03E-02	4,33E-02	6,79E-02	9,97E-02	1,39E-01	1,85E-01	5,00E-01	8,06E-01	9,59E-01	9,96E-01	1,00E+00	1,00E+00
1,00E+02	2,57E-05	1,03E-02	4,34E-02	6,80E-02	9,98E-02	1,39E-01	1,86E-01	5,00E-01	8,06E-01	9,60E-01	9,96E-01	1,00E+00	1,00E+00
5,00E+02	2,57E-05	1,03E-02	4,34E-02	6,80E-02	9,98E-02	1,39E-01	1,86E-01	5,00E-01	8,07E-01	9,60E-01	9,96E-01	1,00E+00	1,00E+00
1,00E+100	2,57E-05	1,03E-02	4,34E-02	6,80E-02	9,98E-02	1,39E-01	1,86E-01	5,00E-01	8,07E-01	9,60E-01	9,96E-01	1,00E+00	1,00E+00

>D50
>D5
>D1



2.4. Values of D_1, D_5, D_{50} and D_{100} for the various lethal and non-lethal deterministic effects

The table below shows the orders of magnitude of the values of D_1, D_5, D_{50} and D_{100} for the lethal and non-lethal (disabling and non-disabling) deterministic effects that occur most frequently in the case of low energy transfer radiation at dose rates of 1 Gy/h and infinity.

D_1, D_5, D_{50} and D_{100} are absorbed dose values corresponding to a risk of occurrence of the effect in a uniformly exposed population with probabilities of 1%, 5%, 50% and 100% respectively.

Table A2.1. Values of D_1, D_5, D_{50} and D_{100} for lethal and non-lethal deterministic effects

		1 Gy/h dose rate				"Infinite" dose rate			
LETHAL EFFECTS	***Organ***	**D_1 (Gy)**	**D_5 (Gy)**	**D_{50} (Gy)**	**D_{100} (Gy)**	**D_1 (Gy)**	**D_5 (Gy)**	**D_{50} (Gy)**	**D_{100} (Gy)**
Death of embryo at age 1 to 18 days	*Embryo*	0.15	0.3	1	4.5	0.12	0.3	1	3.1
Death of foetus at age 19 to 150 days	*Embryo/ fœtus*	0.37	0.6	1.5	3.3	0.36	0.6	1.5	3.2
Death of foetus at age 150 to 270 days	*Fœtus*	1.5	1.9	3.1	4.5	1.5	1.9	3	4.4
Bone marrow irradiation syndrome (no medical follow-up)	*Bone marrow*	1.5	2	3.1	4.5	1.5	1.9	3	4.4
Bone marrow irradiation syndrome (with medical follow-up)	*Bone marrow*	2.3	3	4.6	6.7	2.2	2.9	4.5	6.6
Pulmonary irradiation syndrome	*Lungs*	22	27	40	55	5.5	7	10	14
Gastro-intestinal syndrome (ext. irrad.)	*Small intestine*	9.8	11.5	15	18.9	9.8	11.5	15	19
Gastro-intestinal syndrome (int. irrad.)	*Colon*	9.8	11.5	15	18.9	9.8	11.5	15	19
NON-LETHAL DISABLING EFFECTS	***Organ***	**D_1 (Gy)**	**D_5 (Gy)**	**D_{50} (Gy)**	**D_{100} (Gy)**	**D_1 (Gy)**	**D_5 (Gy)**	**D_{50} (Gy)**	**D_{100} (Gy)**
Severe mental retardation (irrad. of embryo or foetus aged 8 to 15 weeks)	*Fœtus*	0.12	0.27	1	3	0.12	0.27	1	3
Severe mental retardation (irrad. of fœtus aged 16 to 25 weeks)	*Fœtus*	0.24	0.54	2	6.3	0.24	0.54	2	6.3
Microcephaly (0 - 15 weeks)	*Embryo / Fœtus*	0.016	0.06	0.8	7.9	0.016	0.06	0.8	8
Temporary or permanent interruption of ovogenesis[7]	*Ovaries*	0.9	1.6	3.8	8.1	0.8	1.5	3.5	7.5
Temporary interruption of spermatogenesis[8]	*Testis*	0.46	0.54	0.7	0.88	0.46	0.54	0.7	0.88
Cataract	*Lens of the eye*	1.3	1.8	3	4.8	1.3	1.78	3	4.7
Fibrosis	*Lungs*	9	12	20	30	2	3	5	8
NON-LETHAL NON-DISABLING EFFECTS	***Organ***	**D_1 (Gy)**	**D_5 (Gy)**	**D_{50} (Gy)**	**D_{100} (Gy)**	**D_1 (Gy)**	**D_5 (Gy)**	**D_{50} (Gy)**	**D_{100} (Gy)**
Vomiting	*Abdomen*	0.54	0.92	2.2	4.7	0.49	0.84	2	4.3
Diarrhoea	*Abdomen*	0.59	1	3.2	8	0.55	1.1	3	7.5
Hypothyroidism	*Thyroid*	3.5	12	90	500	2.3	8	60	350
Thyroiditis	*Thyroid*	140	300	1200	3800	140	300	1200	3800
Burns	*Skin*	10	15	25	40	8	12	20	30

[7] The model does not differentiate between the two cases (temporary and permanent). Doses of more than 6 Gy result in the complete interruption of ovulation in 100% of cases.

[8] There is no NRPB model for aspermia or oligospermia.