REPORT

INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Enhancing nuclear safety

Methodology used in IRSN nuclear accident cost estimates in France

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ABSTRACT

This report describes the methodology used by IRSN to estimate the cost of potential nuclear accidents in France. It concerns possible accidents involving pressurized water reactors leading to radioactive releases in the environment. These accidents have been grouped in two accident families called: severe accidents and major accidents. Two model scenarios have been selected to represent each of these families.

The report discusses the general methodology of nuclear accident cost estimation. The crucial point is that all cost should be considered: if not, the cost is underestimated which can lead to negative consequences for the value attributed to safety and for crisis preparation. As a result, the overall cost comprises many components: the most well-known is offsite radiological costs, but there are many others. The proposed estimates have thus required using a diversity of methods which are described in this report.

Figures are presented at the end of this report. Among other things, they show that purely radiological costs only represent a non-dominant part of foreseeable economic consequences.

KEY WORDS

Severe accidents, accident costs, methodology

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1. HISTORICAL OVERVIEW OF IRSN STUDIES

In 2005, the French nuclear safety authority requested IRSN to appraise a cost-benefit tool proposed by the utility, Électricité de France (EDF). With decennial visits in mind[1], EDF aimed at ranking by decreasing efficiency the safety modifications under consideration by experts. The objective was to ensure the best safety performance for each euro invested in safety.

As a first step, S3 type modifications and S1 type modifications were distinguished. Indeed, according to EDF, all safety modifications could approximately be allocated to these two categories:

- S3 type modifications are essentially capable of reducing the probability of S3 type accidents. In the conventional S3 accident scenario, the core of the reactor melts; it is impossible to control this core melt and avoid radioactive releases (contrary to the Three Mile Island accident, USA, 1979); operators are led to release the pressure which has accumulated inside the confinement in order to safeguard it. This venting is a controlled operation, releases pass through a metallic filter and a sand filter designed to this effect which significantly reduce the quantity of released radioactivity. The venting is performed 24 to 48 hours after the onset of the core melt which leaves time to evacuate persons which could be most exposed.
- S1 type modifications are essentially aimed at reducing the probability of S1 type accidents. This scenario is considered to be an upper bound, i.e. the worst possible case on a French reactor; at one time it was conceived as the release of 100% of the core inventory, but given the very unrealistic character of this hypothesis, the S1 scenario considered here implies releasing one third of the activity of the core[2] – a very high proportion.

In practice, all possible core melt accidents followed by releases fall between S3 and S1, S3 being a lower bound and S1 an upper bound (see table 1 hereafter).

In each of these two categories of safety modifications, safety gains were measured by the reduction they achieved in the probability of the said accidents, viz. dp_3 and dp_1. The safety-efficiency indices proposed by EDF were:

$\frac{dp_3}{c}$ and $\frac{dp_1}{c}$ where c is the cost of the safety modification.

Modifications belonging to two different categories were compared by considering accident costs. Safety-efficiency indices were then reformulated as:

$\frac{S_3 dp_3}{c}$ and $\frac{S_1 dp_1}{c}$ where S_3 and S_1 were the costs of the corresponding accidents.

IRSN then undertook estimating the cost of these accidents. The result of this work is summarized in table 1 hereafter.

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[1] For the third decennial visit on 900 MWe reactors.

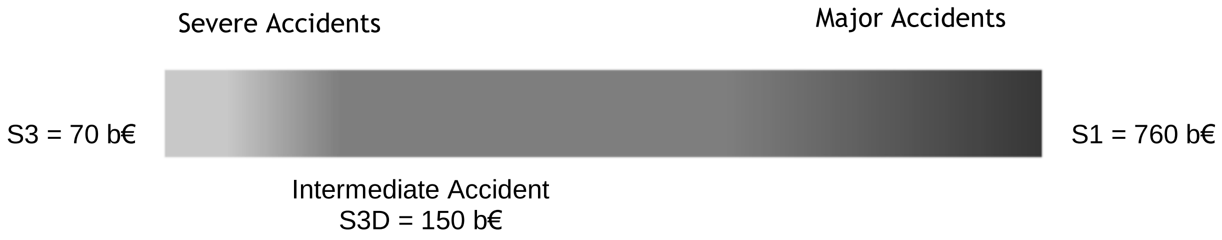
[2] Conventional scenario, release of all rare gases and of 33% of the remainder of the core.

The cost of accidents S3 and S1 was estimated taking into account all identified consequences whether they corresponded to direct radiological contamination or to economic and social consequences less directly material in nature such as, for example, retail stores refusing to commercialize foodstuffs with low levels of contamination or consumers simply boycotting them. In this way, these estimates innovated compared to the great majority of previous publications[3] by taking into consideration, alongside radiological costs, other economic costs which are bound to materialize (see section 4 below).

These estimates have shown that S3 and S1 are of different natures to such an extent that they should not be compared on the sole basis of the ratio of their costs, S3 type accidents featuring relatively mild radiological consequences and significant economic costs whereas S1 type accidents would confront the country to a radiological crisis of major dimensions.

Studies have been continued after 2007 to refine these preliminary results. In particular, the computer code used to calculate radiological consequences was acceptable to estimate effects at short distances, but inadequate to reliably assess the long distance effects an S1 type accident can imply. On the basis of differences identified between the conventional S3 and S1 scenarios, two accident families were distinguished: severe accidents and major accidents. An intermediate S3D accident materialized the limit between the two families and featured 100 times more releases in cesium 137 than the S3 and 100 times less than the upper bound S1 (the ratio between S1 and S3 is indeed close to 10,000 in terms of rejected cesium 137). Model accidents for these two families were evaluated, especially by improving knowledge of image effects[4] and of effects on the production of electricity[5]

Table 1: 2007 estimates (median values in billion euros)



Source: Examen de la méthode d'analyse coût-bénéfice pour la sûreté, Rapport DSR N°157, annexe 4, Réunion du Groupe Permanent chargé des Réacteurs nucléaires du 5 juillet 2007, available in French on the IRSN website.

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[3] See for example, OECD-NEA, Methodologies for Assessing the Economic Consequences of Nuclear Reactor Accidents, 2000

[4] See section 8 below. In general, an image effect occurs when the public turns its back on a product because of more or less unfounded fears which globally constitute the loss of reputation of the product.

[5] See section 9 below.

2. PRESENTING GLOBAL RESULTS

Nuclear accident costs continued to be analyzed; results tended to confirm the general results obtained in 2007: the nature of the severe and major accidents, as well as the order of magnitude of their costs, did confirm differences previously identified between the limit case scenarios S3 and S1. This led to global figures being published in 2012-13. This section explains what are global results and how their implications should be understood.

2.1. The nature of global accident costs figures

By global figure we mean a cost which aims at being representative, at covering a large number of circumstances characterized by numerous parameters. These parameters can be grouped in broad families:

- The source term, i.e. the composition and kinetics of the release. A radioactive release from an electricity producing reactor contains dozens of different components, gases and particles (aerosols), the most important for our subject being cesium (cesium 134 and 137) and iodine (in gaseous or molecular form). More severe releases should take place within short episodes while more limited releases could last for several days[6].
- Climatic conditions play a determining role since the wind direction and its possible changes during the course of plume dispersion will determine which zones are affected and those which are spared radioactive fallout. Precipitations may wash the plume along its route and cause larger fallout in some places.
- The geographical location of the site influences consequences in various ways. For example, a site located on a sea shore should *a priori* entail less severe consequences because the wind can blow the plume onto the sea with minimal consequences compared to radioactive fallout on land. This is precisely what happened several times during the sequence of events which took place during the Fukushima accident. Site location also matters because of the greater or lesser density of population around the site, in particular the presence of large cities liable to be contaminated. Lastly, human activities can be more or less profitable, notably within the agricultural sector, and therefore have larger or smaller potentials for losses.
- Reactions of the general public, businesses and other economic players can aggravate or minimize the extent of losses due to a nuclear accident. These phenomena are often grouped under the term resilience, i.e. the greater or lesser capacity to bounce back. Some observers have suggested that the resilience of French people would be lower than that of the Japanese confronted to the Fukushima accident[7]; however, nothing solid substantiates such an opinion. Similarly, efficient responses from the

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[6] In Chernobyl, quite to the contrary, the release was very large *but* continued over some ten days, a scenario which seems impossible on the present French fleet of reactors.

[7] « Un accident nucléaire, c'est la fin de la démocratie », Antonio Pagnotta, photojournalist, Le Monde, 10/03/2013

authorities, in particular concerning the most prominent subjects such as the defense of agricultural activities, of tourism or of the existing fleet of nuclear reactors can help reduce accident costs.

- The proportion of nuclear electricity and therefore the date at which the accident occurs in relation with the demography of the fleet of nuclear reactors is also important, particularly as regards the impact of the accident on electricity production. If electricity production is less intensely nuclear, or if the replacement of reactors is largely on its way, consequences may be less drastic and the increase in electricity bills of French consumers more limited.

Providing masses of results corresponding to the endless combinations of these many parameters would be particularly unhelpful. The reader would not know what to think. For this reason, one accident was chosen within each accident family as a model intended to represent the family and thus make it possible to understand the many possible variations within the family.

As indicated above, it was clear as early as 2007 that presenting one accident, as opposed to two as done here, would conceal essential differences. The two accident families mentioned in section 1 have very different characters which were deemed essential to explain. Two accident families have thus been distinguished; one set of results is given for the “severe” accidents and one for the “major” accident. Each one is intended to represent:

- all possible releases within the family;
- all meteorological conditions;
- all relevant sites; and
- all possible accident dates within the lifetime of the fleet of nuclear reactors.

One therefore realizes that one specific scenario may deviate from the representative figures, and possibly significantly so. This in no way questions the value of publishing global figures, a value which is now detailed and should clarify why they were published.

2.2. Global figures suggest a picture of the different components of a nuclear crisis

A global and quantified understanding of the overall picture of a nuclear crisis can provide crisis managers with an ex-ante vision of the major issues to be addressed. For some non-specialist observers, a nuclear accident is first and foremost a public health challenge. Cost estimates performed by IRSN show this to be inaccurate, especially for severe accidents. In such a case, releases being delayed in time and filtered by appropriate devices, economic aspects largely dominate radiological costs. Cost estimates offer a *quantitative* vision of the phenomenon and advocate addressing these economic aspects at the preparation stage in accordance with their probable costs; this allows crisis management to take the necessary steps at an early stage and thus protect citizens from having to bear costs heavier than necessary.

2.3. Global figures offer a basis for public decisions concerning safety

Global costs for nuclear accidents also shed light on the extent of losses, i.e. on the value of safety.

Figures offered in this report exceed previous estimates which generally only consider radiological costs (see sections 4.1 à 4.4 below). With higher accident costs, the value of safety appears higher than expected previously. The willingness to invest in the prevention of nuclear accident must then be revised upwards. All things equal, underestimating accident costs leads to retain residual risks above the optimum. A better knowledge of accident severity allows better adjusting the level of safety.

In addition, results show that severe and major accidents are of different natures. This should also bear on decisions. It no longer appears feasible to address these two categories of accidents in the same fashion[8]. In particular, one of the important conclusions of global figures is that the lower probability of major accidents may not necessarily compensate for their catastrophic character. Working for safety while ignoring, because of their extremely low probabilities, the catastrophic character of the most severe accidents would, again, imply deviations from decisions taken with the benefit of full information.

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[8] In the future, it may be necessary to distinguish more than two categories of accidents.

3. MODEL ACCIDENTS AND ASSOCIATED RADIOACTIVE RELEASES

3.1. Range of accidents considered in IRSN PSA2 studies

Considered releases are based on the PSA level II studies conducted by IRSN, i.e. the in-depth study of possible radioactive releases from a French electricity production reactor. Cause and event trees are established starting from all possible internal initiators leading to 44 large accident families. Releases are identified for both the production and shutdown states of the reactor. The following table lists these states (acronyms used by specialists are explained below the table).

Table 2: Releases and accidents in the IRSN PSA2

Type of release	Accident family	Production states	Shutdown states
Limited releases	Limited fuel damage	x	x
Releases through natural confinement leaks	Successful in vessel reflooding; confinement is not breached	x	x
	No basemat penetration 15 days after ART	x	
Loss of confinement before 24 hours	Heterogeneous dilution		x
	Small breach, beta mode/phase B	x	x
	Induced SGTR	x	
	Large breach, beta mode/phase B	x	x
	Small breach, beta mode/phase D		x
	Equipment hatch initially open		x
	Large breach, beta mode/phase D		x
	In vessel steam explosion	x	
	Ex vessel steam explosion		x
	Alpha mode		x
	Heterogeneous dilutions	x	
	U5 filtered containment venting phase D	x	
	Initial SGTR	x	
	Consequences not evaluated (STR, ATWS – PPO)	x	
	Small breach, beta mode/phase D	x	
	Combustion/pressurization phase B	x	x
Loss of confinement before 24 hours after ART; releases greater than the S3 source term	V-LOCA	x	
	Small breach, beta mode/phase B	x	x
	Containment ruptured by pressurization, CCB	x	x
	Equipment hatch initially open		x
	Small breach, beta mode/phase D		x
	Large breach, beta mode/phase B	x	x
	Initial SGTR		
	Ex vessel steam explosion		x
	Induced penetration leak phase D	x	x

	Large breach, beta mode/phase D		x
	Direct containment heating	x	x
	Combustion/pressurization phase B	x	
	In vessel steam explosion	x	
	Inappropriate operation (water supply)	x	x
	Induced penetration leak phase B	x	
	Alpha modes	x	x
	Small breach, beta mode/phase D	x	
Loss of confinement after 24 hours after ART ; releases lower than the S3 source term	U5 filtered containment venting phase D	x	x
	Basemat penetration	x	x
	In vessel reflooding succeeds, loss of confinement	x	x

Source : EPS2/REP900 Version 4.0, Rapport de synthèse, Tome 2, Résultats en conséquences radiologiques, Rapport IRSN/DSR/SAGR No. 41, Rapport EPS2/NS1/2009-01
AAR: Automatic Reactor Trip
SGTR: Steam Generator Tube Rupture
TAM : tampon d'accès matériel
(SPR, ATWS - PPO) secondary pipe rupture, Anticipated Transitory without scram – Primary Pump Overpressure)
V-LOCA: Loss Of Coolant Accident; mode V refers to the bypass of the containment through pipes leading outside the confinement.
CCB : Corium Concrete Interaction
U5: venting procedure through a metallic filter and a sand filter designed to reduce radioactivity by a factor 10000.
Mode ß: isolation failure (small or large), initial or rapidly induced; the Rasmussen report, published in 1975 under the reference WASH 1400 and NUREG 75-014, was the first to propose a classification of containment failure modes including five main modes designed by Greek letters. It is still in use today.
Phase B and D: the evolution of the accident inside the containment is divided into several phases. The progression towards the core melt corresponds to phase A, the progression of the accident inside the vessel after the core melt to phase B, phase C to the instant when the vessel ruptures and phase D to the long term phase after this rupture.

3.2. Releases of aerosols by accident families

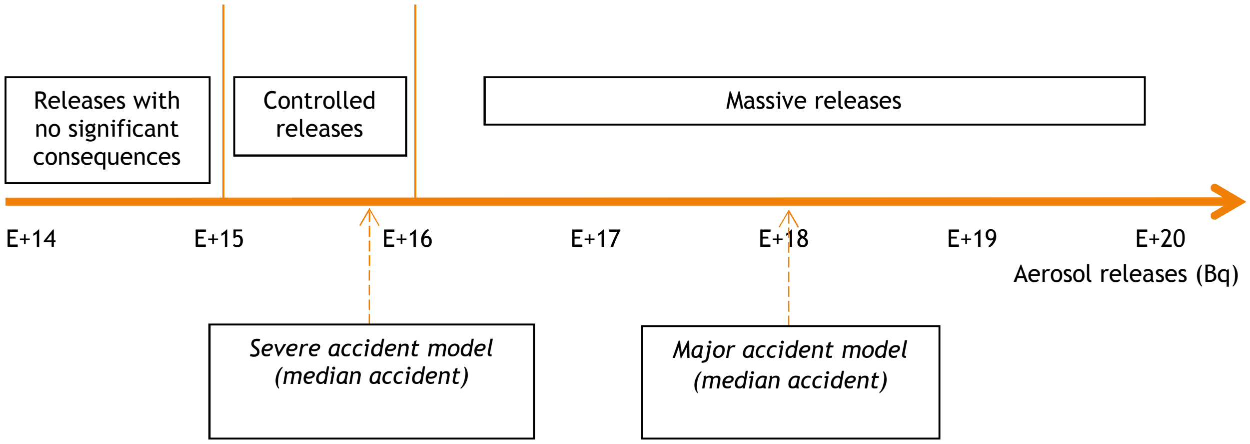
Released aerosol activity is a physical indicator of the severity of releases. The IRSN PSA2 for 900 MWe reactors, the most common in the French fleet of reactors, establishes that this indicator can vary between 10^{15} Bq or less, up 10^{19} Bq and possibly more, i.e. a ratio of more than 1 to 10,000. This indicator appears to be the most relevant for the estimation of health consequences and land contamination.

As indicated in section 1, as early as the preliminary 2007 estimates, it appeared that the least severe accidents (S3 accident, with aerosol releases in the range of 10^{15} Bq) were very different in nature from the most severe accidents (aerosol releases in the order of 10^{19}Bq). For the sake of economic studies, two accident families have been distinguished:

- accidents called "severe": releases are more or less controlled, as in the conventional S3 scenario described above; this accident family corresponds to releases with aerosol activities between 10^{15} Bq and 10^{16} Bq;
- accidents called "major": releases are massive, typically relatively concentrated in time; this accident family corresponds to releases with aerosol activities between 10^{16} Bq and 10^{19}-10^{20} Bq in the case of 900 MWe reactors.

This is graphically represented on figure 1 hereafter.

Figure 1: Accident families and aerosol releases for 900 MWe reactors



3.3. Model accidents intended to represent accident families

Having distinguished these families to give a simplifies sketch of the spectrum of possible nuclear accidents, the objective is to offer as realistic a picture as possible of each family while avoiding any focus on extreme cases. Focusing on the most extreme (and least probable) release and on its most severe expression (due to exceptionally unfavorable climatic conditions), would misguide the decision-maker[9], promote suboptimal decisions, cause public funds to be wasted and therefore mean unnecessary costs for all French people.

Ideally, one should estimate median costs for each family, i.e. costs having 50% chances of being below the cost of any particular randomly chosen case, and 50% chance of being above it. To achieve this, one would have to know the entire statistical distribution of these costs with respect to all their parameters. This is out of reach today. Therefore, for each family, a median *release* scenario was established as a first step, a "median" cost then being pursued for this type of release. A model accident is thus defined for each family; describing this model provides an understanding of *the major features* of accidents in the family.

As far as releases are concerned, the median character within the family is determined on the basis of the IRSN level II PSA for 900 MWe[10] reactors. It is *the entire set* of results of this PSA which allows defining median releases[11]. The set of all possible releases results from the detailed study of very numerous possible scenarios[12];

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[9] The wording decision maker is used in decision theory but does not necessarily represent a person. To be entirely rigorous, it would be advisable to refer to the "decision process". This will generally involve many persons. In this sense, misguiding the decision maker means misguiding many people taking part in the decision process.

[10] EPS2/REP900 Version 4.0, Rapport de synthèse, Tome 2, Résultats en conséquences radiologiques, Rapport IRSN/DSR/SAGR No. 41, Rapport EPS2/NS1/2009-01

[11] Knowing 101 values drawn randomly and ordered (in increasing or decreasing order), the median corresponds to the 51st point; modifying points different from this one can modify the ordering and thus the point representing the median and therefore the median itself.

[12] For example, with 44 aggregated families the distribution of each family being represented by 5 points (with probabilities 1%, 5%, 50%, 95% and 99%), the distribution of releases is defined by 220 points.

strictly speaking, the median point has no reason to correspond to one of the points which make up the distribution curve but is generally positioned between two such points. It is thus understood that what is relevant is the release itself, not the scenarios which imply releases of that order. In general, future progress could consist in estimating the cost of a finer set of release[13].

The model accident for the family “major accidents” corresponds to releases with aerosol activities of 10^{18} Bq. This by itself is sufficient to run the simulations; however, a precise accident scenario is concerned, *Direct Containment Heating*. A description of this accident is given in appendix 1 although, as just explained, this description is in no way essential for an economic estimation.

The model accident for the family “severe accidents” was determined on the basis of an upper bound for the family[14] and lower bound approached by the conventional S3 scenario[15].

The position of the model accidents within the range of possible releases is indicated on figure 1.

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[13] For example, E+14 Bq, E+15 Bq, E+16 Bq, E+17 Bq, E+18 Bq, E+19 Bq, E+20 Bq.

[14] The size of the release which acts as limit between severe and major accidents, namely E+16 Bq, is approximated by the actual EVHC scenario meaning Steam Explosion outside the Vessel (explosion de vapeur hors cuve).

[15] The activity of releases is the most important indicator but their kinetics can also play a role. While major releases occur rather rapidly (for example, within 2 hours), severe releases can extend over several days, most of the activity being released during the first 24 hours.

4. COST ESTIMATION METHODOLOGY

4.1. The "consequences" approach

The first accident studies adopted a "consequences" approach; they mainly focused on radiological effects of releases and had in mind the emergency management of a hypothetical nuclear crisis involving radioactive releases. Here is a short historical account of the development of these studies.

In 1975, the Rasmussen report (WASH-1400) offers accident probabilities for civilian nuclear activities in the United States; it also suggests accident costs; they range from $1 million to $14 billion. The report is based on probabilistic safety assessments (PSAs), techniques which were advanced for the time and had been developed in the framework of military nuclear activities. The figures are quickly criticized despite their novel character. Only four years afterwards, the Three Mile Island accident occurs in the United States and the safety authority requests a new report. This is published in 1982 and estimates that the cost could amount to $314 billion in the worst case (CRAC-2[16]). The computer code used for this exercise gives rise to MACCS; this code is used afterwards for a study dated 1990 (NUREG-1150[17]) still considered today based on good methodology. In parallel, Europeans conduct the MARIA project (Methods for Assessing the Radiological Impact of Accidents) which gives rise to the Cosyma code (Computer system for MARIA); the first PC version of the code is documented as early as 1994[18].

These two codes essentially calculate radiological consequences; they can be seen as tools pertaining to a third level of PSAs. Level I PSAs study failure modes leading to core melt; one of their emblematic results is a core melt probability. After the Three Mile Island and Chernobyl accidents, this appears insufficient because the possibility of releases must be seriously considered. Level II PSAs aim at characterizing phenomena arising after a core melt; they calculate the probability and nature of possible radioactive releases. Consequence codes go beyond such probabilities and aim at quantifying consequences of a radioactive release, essentially radiological consequences. One can thus use the term level III PSAs.

A level III PSA includes a code[19] which calculates the dispersion of radioactive releases from the site of the accident and the deposition of radioactive particles onto the ground depending on climatic conditions; a code for the transfer of radioactivity within the food chain; and a code which calculates health effects by combining exposure to the radioactive plume, ingestion of contaminated foodstuffs and residual ground shine on the people who live in contaminated areas.

A probabilistic PSA3 code includes an input interface for "fixed" data such as meteorological data of the year; it calculates consequences by randomly drawing within these meteorological data. For example, the PC version of

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[16] CRAC-2 report by U.S. NRC & Sandia National Lab, 1982 ; NUREG/CR-2239

[17] Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants, December 1990, NUREG-1150

[18] PC COSYMA: An Accident Consequence Assessment Package for Use on a PC, final report. Jones, J. A. Luxembourg Office for Official Publ. of the Eur. Communities, 1994, VII, 63 S; EUR 14916 : Radiation protection.

[19] The term "code" is employed by professionals and designates a series of computer programs.

the European Cosyma code, PC Cosyma 1995, draws 144 sequences equally spaced within one year of data[20] which allows estimating a probability distribution of estimated consequences.

Other fixed data are needed such as land-use, population distribution, etc.

Finally an interface takes into account the intervention of emergency squads and the management by government of the post-accidental phase. Such “countermeasures” are taken to reduce the impact of accident consequences. Emergency countermeasures essentially consists in: evacuating people closest to the accident site when there is enough time; confinement (at home or inside buildings) which concerns people affected by the radioactive plume but residing further away from the site and therefore a priori less exposed; and the distribution of stable iodine tablets. Another essential countermeasure consists in banning consumption and sale of foodstuffs beyond a given level of contamination. The more demanding the ban (the lower the limit concentration), the larger the quantity of banned foodstuffs, the lower the doses ingested by the people and the lower the health consequences; however, costs can become very high for agriculture.

From an economic point of view, the most important cost items are sanitary consequences and agricultural losses. The consequences approach, as exemplified by a level III PSA code, provides a probability distribution of consequences with respect to climatic conditions. These distributions can be detailed or summarized by their means or their medians.

Given the quantities, it is relatively easy to multiply them by prices (or unit costs) to obtain accident costs. However, with such an approach, there can be no costs when there is no radiological contamination:

zero Becquerel = zero cost

Therefore this approach only covers part of the costs, namely those linked to the presence of excess radioactivity. It thus underestimates the severity of the accident for the economy and therefore the value of prevention as explained hereafter.

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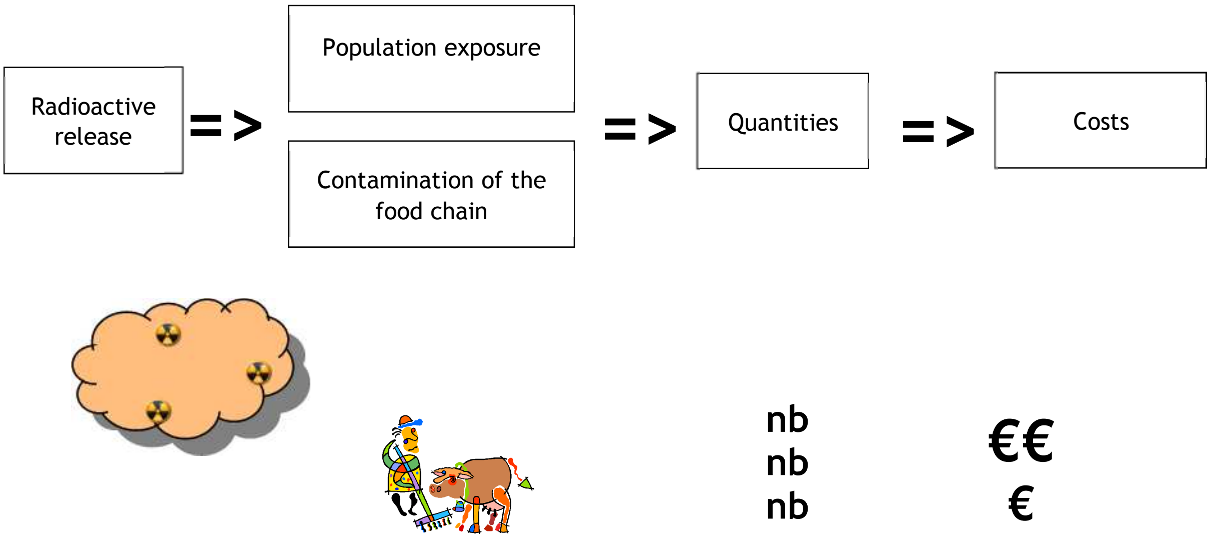
[20] Approximately every 60 hours, i.e. every 2.5 days.

Figure 2: The radiological consequences approach



4.2. The economic approach

Contrary to the previous approach, the economic approach considers all possible effects, including radiological effects, but also all other possible effects leading to costs. It aims at comparing a situation without accident and a situation where the accident has taken place.

In the course of such a comparison, all costs must be taken into account — a crucially essential point. Indeed an economic accident cost is bound to be compared, sooner or later, with the cost of the prevention of the concerned accident. If therefore the cost of the accident is underestimated, so will be the value attributed to its prevention. As a result, prevention expenses will be lower than they should have been, all other things equal, and the residual risk retained will be higher than what it should have been, all other things equal.

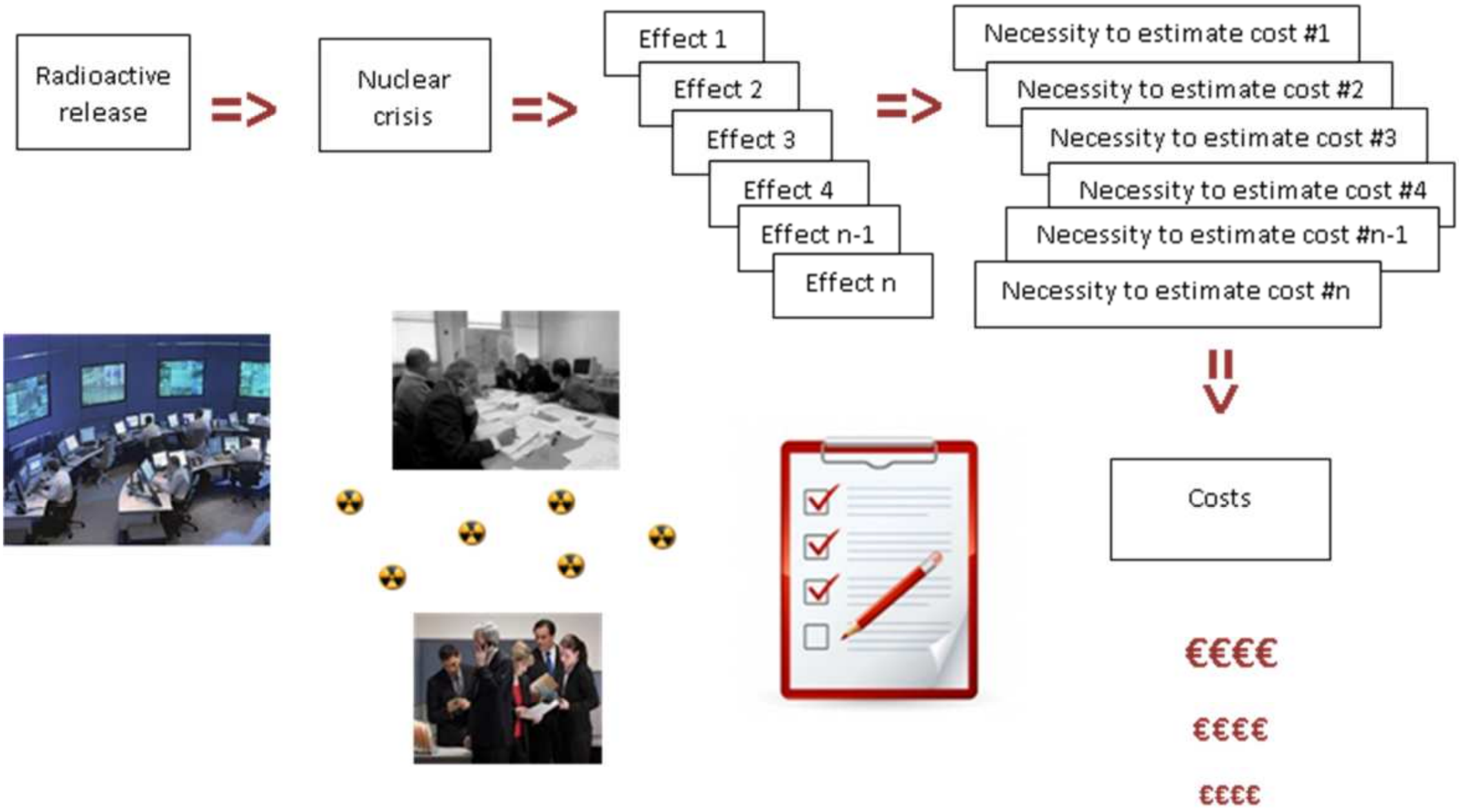
Thus, the economic approach starts with listing the entire set of all possible effects of the crisis generated by a nuclear accident, without any preconception about these effects. The objective is to be descriptive and as comprehensive as possible.

After having established this list, it is necessary to evaluate the cost of each item in the list. Three aspects should be underlined at this point:

- whether such an estimate is difficult to provide or not cannot justify disregarding the corresponding effect; indeed, neglecting one type of impact amounts to ascribing it a zero value, i.e. to underestimate, *in fine*, the value of the accident and therefore the value of its prevention;
- in a very general fashion, the method is always the same: estimate all costs, everywhere, for all parties;
- besides and very generally, any estimation process is clarified and refined by breaking down the cost under consideration into components.

The method can thus be illustrated by the following figure.

Figure 3: The economic approach



The next figure details the differences which have just been spelled out with the consequences approach.

Figure 4: Differences between the consequences approach and the economic approach

Consequences approach (PSA3)		Economic approach
zero Becquerel = zero cost		zero Becquerel = possible costs
Physical and medical phenomena which can be replicated Modeling of physical phenomena, based, as far as possible, on experiments	≠	Includes, in addition, social phenomena not amenable to an experimental approach Economic modeling

These points are now detailed.

4.2.1. Listing all costs

This task should be comprehensive. This is perfectly clear from a methodological point of view but in practice, cost items are always necessarily omitted. Indeed it is impossible to enter into all details, regional and local or even finer; estimating costs does not consist in writing the saga of all individual stories of all the victims — even if it were possible.

One should actively look for all possible cost items and ensure that those disregarded remain small relative to other cost items and to the total cost. For example, in the present case, one can pursue the reasonable objective that all costs of above €1 billion are considered and estimated.

Even thus, a difficulty remains: how can one guarantee before having appraised it, that a given cost item is actually below such a threshold? One can only rely on a more or less implicit estimation exercise based on professional expertise.

In conclusion, whatever the attention given to this phase of the estimation process, it contains a bias towards underestimation because, while identifying cost items, one can only, in practice, miss one or two[21]. Remaining conscious of this bias should limit its extent.

4.2.2. The need to estimate corresponding costs

When one type of impact has been identified, it is imperative to estimate it. Accepting not to provide a figure for such or such cost item is tantamount to ascribing it a zero cost. It is impossible to commit a larger underestimation! No other estimate however imprecise will ever underestimate the corresponding costs by a larger gap[22]…

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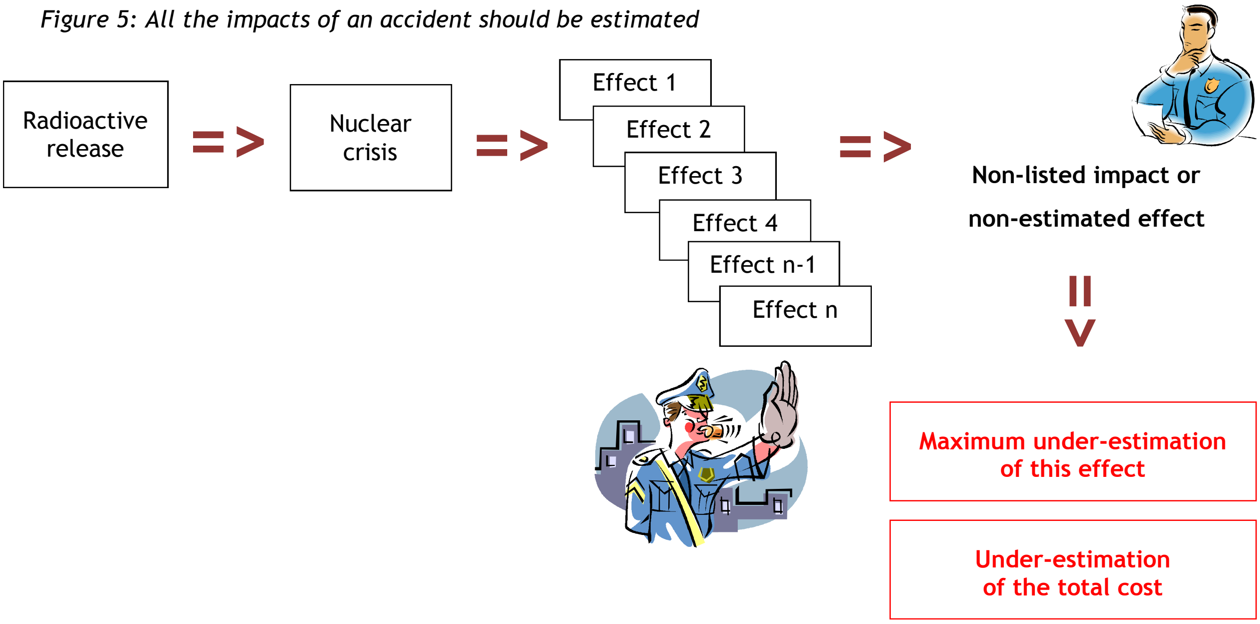
[21] There exists a comparable risk in engineering: the costs of a project generally feature a final cost item called *contingencies;* it is generally expressed as a percentage of costs estimated without contingencies; such percentages vary from sector to sector and are the object of a professional consensus based on experience.

[22] Granted, there remains a possibility for costs to be overestimated by a larger amount (i.e. more than doubling the true cost). Therefore, the methodological requirement to provide a figure by no means allows indulging in large overestimations …

Figure 5: All the impacts of an accident should be estimated



As examples of identified effects which are *a priori* difficult to estimate one can mention the impact on tourism and psychological effects.

4.2.3. For each identified effect, estimate all costs

Having recognized the need to estimate all impacts, all types of consequences, it is again necessary to strive at being comprehensive while individually estimating each cost items. From an economic point of view, for example, it is recognized that a “direct” effect has “indirect” implications.

> For instance, as far as tourism is concerned, the image effect of a nuclear accident will directly imply a decrease in tourist arrivals in France. Thus, hotels, restaurants, camping grounds, tourist attractions, etc., will experience lower levels of activities. This constitutes the direct effect (in economic terms).
>
> In the normal course of their activities, the corresponding businesses purchase goods from other businesses. For example, a hotel may use the services of an industrial laundry factory; a tourist attraction may subcontract cleaning and place orders with a print shop for its leaflets. A direct reduction in tourist activity (hotel nights for example) causes an indirect reduction in the activity of these providers (less laundry, cleaning or printing activity). These indirect effects cascade within the economy (for instance, the industrial laundry factory reduces its purchases of chemical products and its reliance on transport and delivery services). Globally all these effects constitute the indirect cost (in economic terms).
>
> Finally, all the declines just mentioned, direct and indirect, affected the earnings of households. For example, the hotel hires some employees part-time instead of full-time. As a result, households earn lower revenues, they reduce their consumption, which in turn generates further reductions in business activity. This is called the induced effect.

For each cost item, it is therefore necessary to perform a triple estimation including direct, indirect and induced effects.

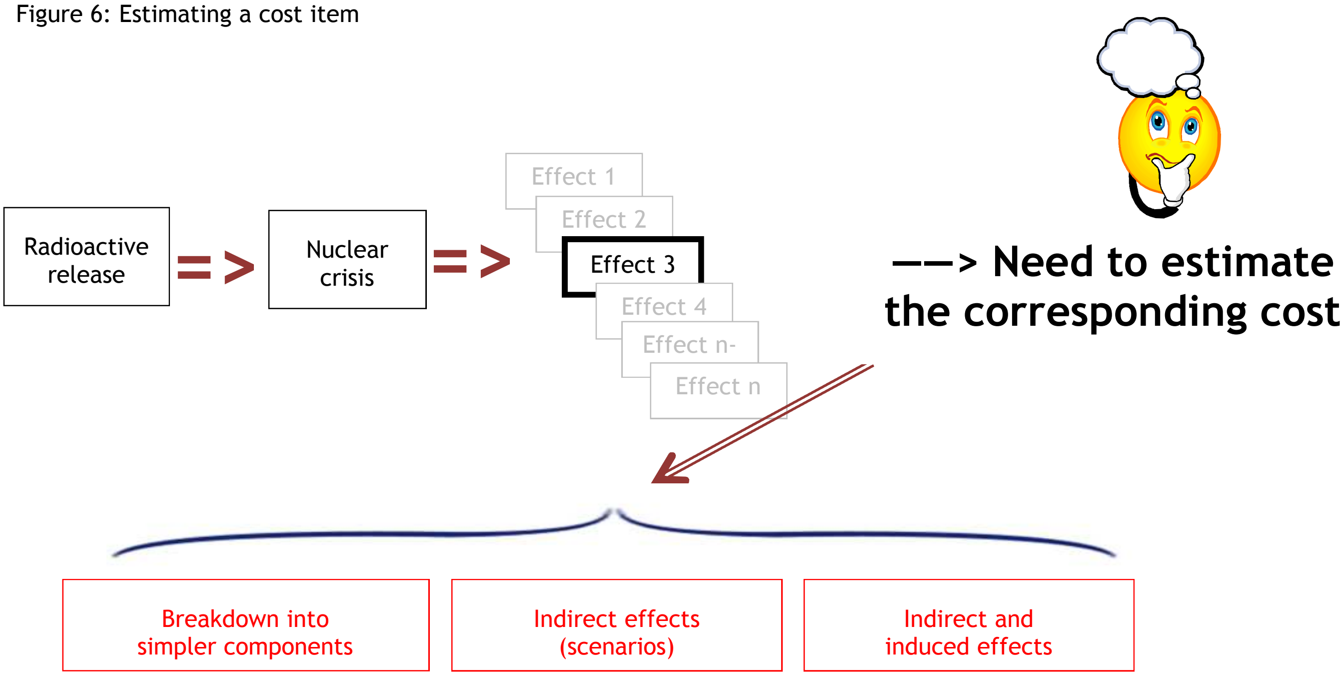
Calculating direct effects requires a scenario detailing the way the concerned quantities would be affected; such a scenario is an essential input. In the framework of the studies conducted by IRSN, scenarios have been established on the basis of internationally available data for similar phenomena, for example for image effects. These scenarios may be refined in the future by specialized studies of the concerned activity sectors.

Indirect effects are classically calculated based on exchanges between economic sectors as reflected in the national accounts (the so-called input-output tables or the input-output matrix of the economy). In the short or medium run, it is difficult to see how an economy could escape such indirect effects; in the long run, it is possible that national economic activities would find other forms of expression and that compensating activities would emerge. Estimates computed by IRSN do not enter into this level of refinement. Besides, calculating indirect effects must also take into account “leakage” outside the national economy; indeed, some indirect effects are bound to materialize in the accounts of foreign providers; they should not be taken into account in an estimate with a perimeter limited to France.

In quantitative terms, indirect effects depend, strictly speaking, on the sector initially impacted. Indeed, the coefficients of input-output matrices, i.e. the rates at which sectors in the economy purchase goods produced by other sectors, do vary from one sector to another. However, the impact on the global multiplier is not spectacular and taking an indirect effect of 80% is a quick way to derive an indirect cost. Thus, taking into account the indirect effect, the overall reduction raises to 180% of the direct impact. The induced effect is taken around 10% of this amount. In total, considering indirect and induced effects approximately amounts to doubling the effect of the initial direct reduction. For global estimates, this level of precision is sufficient since probabilistic values are estimated; in other words, the refinement which could be provided by a precise computation would not modify practical implications of the estimates for the concerned people and decision-makers.

The estimation method for a cost item is illustrated on figure 6 which also features the breakdown mentioned in the following section.

Figure 6: Estimating a cost item



4.2.4. Breaking down a cost into components

Breaking down a quantity into simpler elements is not specific to economy estimation, but the method appears particularly efficient for this type of exercise.

For instance, having identified the existence of image effects, one could provide a global image effect, with no details, no structure by activity type, and therefore no explicit vision. This could for example be estimated summarily by a reduction in percentage applied to GDP. On the contrary, it was deemed useful to study the phenomena more in depth; the main identified components are:

- image effects concerning uncontaminated food products, due to precautionary attitudes on the part of intermediaries (foreign importers or national retailers) or a simple refusal to buy on the part of consumers themselves;
- the reduction in tourist activity;
- the impact on other French products, especially exports from the nuclear power sector.

This is a notable improvement compared to an approach without any breakdown. Again, one could be content with providing a global estimate for each of these components; on the contrary, analyzing things more in depth, main cost items were distinguished within each component thus leading to a structured picture of the effect under consideration. For instance, in the case of the impact of a nuclear accident on the French tourism sector, the following components have been distinguished:

- domestic tourism, i.e. the tourism of French people in France;
- European tourism, i.e. European tourists visiting France;
- and international tourism which refers to all other tourists coming to France.

Structuring the phenomena in this way provides an understanding; for example it is possible to point out that substituting another tourist destination to France is much easier and less costly for international tourists than for domestic tourists.

A greater understanding of elementary components obviously allows better quantitative estimates. Ideally, subheadings being fairly well sketched out, their estimation can be more precise; reconstructing the global effect from its components is more accurate; with the additional advantage that residual errors can compensate from one component to another.

It is now necessary to give a detailed description of the cost items retained in the study.

4.3. The cost items

The following table gives the list of cost items considered in the IRSN study.

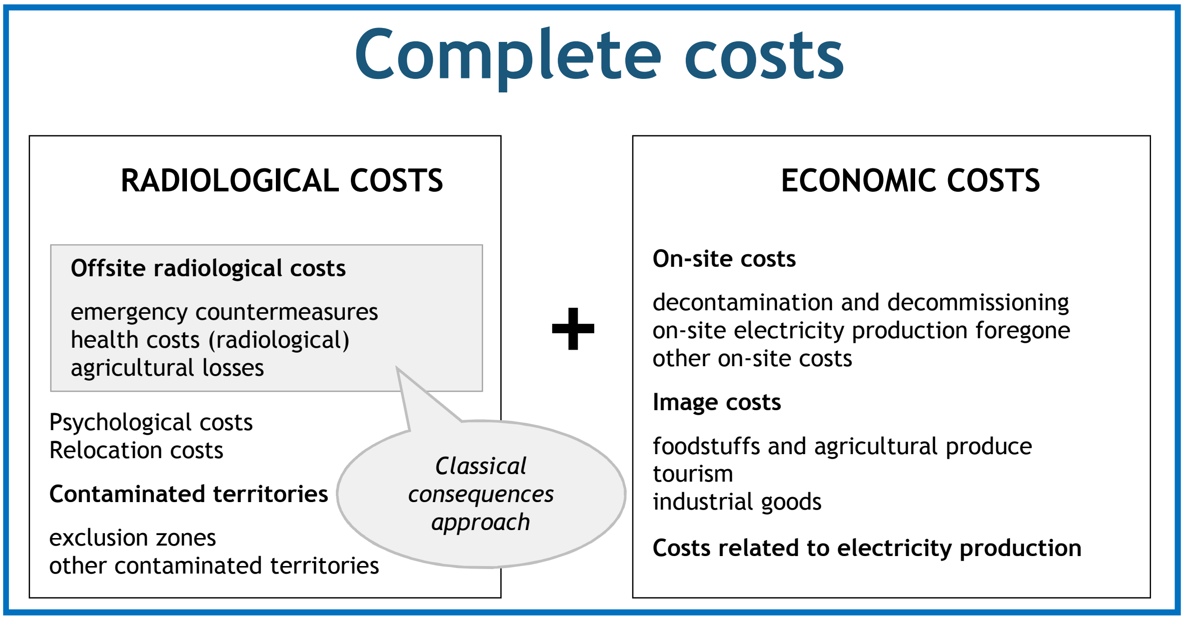
Table 3: Five main components, 14 detailed cost items

Item	**Comments**
Contaminated territories	
Exclusion zones	Costs related to radiological refugees (people who lived in exclusion zones); cost of land considered as capital (no willingness to pay for a "value of motherland" is included)
Other contaminated territories	Based on feedback from Belarus; takes into account the actual costs of contamination and the financial support provided to victims, such transfers acting as proxy for the detriment of people living in such territories.
Offsite radiological costs	
Emergency countermeasures	Cost is marginal within this component.
Health costs (radiological)	In addition to exposure to the radioactive plume, they strongly depend on the quantity of contaminated food ingested by the population. A boycott by consumers and retailers is considered possible.
Psychological costs	Mainly lost workdays and costs of long-term treatment. No allowance for the suffering of patients (i.e. no willingness to pay beyond purely economic costs).
Agricultural losses	They strongly depend on acceptable concentration limits or on a boycott by consumers/retailers.
Cost of relocation	Depends on the number of people concerned and on the distance between housing built for refugees and existing networks
Image costs	
Impact on food and agricultural products	Affects marketable foodstuffs fit for consumption; based on the feedback from events such as the mad cow crisis, the bird flu or the Spanish cucumber crises in 2011 in Europe.
Impact on tourism	Based on crises having affected tourism worldwide during the past 15 years.
Reduction in other exports	Based on experience gained from the Fukushima accident, adapted to the French situation.
Costs related to electricity production	The most plausible scenario, given the French situation, is a reduction in the lifetime of reactors.
On-site costs	
Decontamination and decommissioning	Based on the feedback from Three Mile Island, as reported by the American consultancy ABZ Inc.
Replacement electricity	Corresponds to the ex-ante production of the lost reactor and of other reactors on site which could be stopped for several years.
Other on-site costs	Marginal compared to the preceding items

4.4. Radiological and economic costs

Within the cost items listed above, one can distinguish radiological and economic costs as follows:

Figure 7: Radiological costs and economic costs



Observe that the classical PSA level III approach only covers part of possible costs. The quantification given below shows that it generally represents a relatively low proportion of costs.

These two types of costs are clearly of different nature:

- Emergency countermeasures, beyond costs borne by the authorities, imply disturbances and income losses for the people concerned during the time of their (temporary) evacuation.
- Health costs relate to people. They essentially correspondent to cancers, lethal or not, which occur several years after the accident (for thyroid cancers) or several decades after (for the majority of other cancers, according to present knowledge). They are due to exposure to the radioactive plume, to ingestion of contaminated foodstuffs and to residual ground-shine in contaminated zones.
- Agricultural losses will be felt immediately and very painfully so for the concerned producers. They will entail income losses, clearly, but also, in some cases, the profound modification of an entire way of living.
- Psychological costs essentially correspond to ensuing sick-leave and to long term psychiatric treatment. Affected persons will suffer from these ailments, an aspect not accounted for in present economic costs. These persons are clearly victims of the accident.
- Strongly contaminated territories will represent a national loss but will also give rise to potentially high numbers of radiological refugees; these will have to experience the hardship of emergency shelters, the rigors of temporary housing in locations which they will not necessarily have chosen and, finally, the need to reestablish a new life in potentially difficult conditions.

- Finally, moderately contaminated areas do not necessarily imply relocation but force inhabitants to modify their lifestyle as is the case in Belarus. There is no return to normal, to the *status quo ante*, but the need to adapt to a new life; this may sometimes be viewed as degraded, possibly as stigmatizing.

In all these instances of radiological costs, human suffering underlies estimates quantified in monetary terms. This is not the case with economic costs; such costs are not marked by the same sort of overtone; they do not carry the same human significance, in any case not in the same proportions:

- costs related to the production of electricity will give rise, in the course of time, to increased electricity bills for the French people; a comparable rise in the cost of fossil energy has already occurred several times in the past and does not lead to unsurmountable difficulties, particularly because the cost is spread out over a large number of people. To help picture the situation, if the corresponding costs were €65 billion over 10 years, the bill would amount to about €100 per Frenchman and per year for 10 years which is not directly comparable to the variety of suffering previously described for "human" costs; it is not negligible, but remains tolerable by many French homes while schemes could be devised to protect the most fragile households.
- Image costs would first be borne by the businesses directly affected. But because of the cascading effects so will the entire economy, it is likely that corresponding costs would, as those mentioned above, be largely spread out among all Frenchmen.

It is thus not only legitimate but necessary to distinguish these costs because of they are of different natures.

4.5. Costs are estimated from the point of view of France

To take into account all costs means: all costs, all the time, everywhere and for all involved parties. It is however necessary to determine the estimation perimeter: in the present case, costs are estimated from the point of view of France. More precisely:

- Radiological costs are estimated independently of the location where they occur; for example, agricultural losses are not localized, they can affect French agriculturalists or agricultural businesses located outside the national territory but affected by the contamination[23].
- Economic costs are estimated from the only point of view of France. Thus, effects on the production of electricity are limited to the French nuclear fleet of reactors whereas substantial costs would probably be borne by other fleets of reactors[24]. The same is true for negative image effects which could affect areas neighboring the French territory whose agricultural productions and tourism could experience non-negligible losses. It is also the case for positive image effects or, in other words the substitution effect which countries other than France could take advantage of. For example, wine producers of other countries could benefit from better sales; competing tourist destinations in Europe or elsewhere could benefit from the transfer of tourists fleeing France[25].

4.6. "Median" costs

The considered accidents correspond, as pointed out earlier (3.2 and 3.3), to releases which are median with respect to the spectrum of possible radioactive releases. The corresponding estimates aim at being median in the following sense.

As far as radiological costs are concerned, the median is essentially located by realizing random drawings within meteorological data. One observes that distributions — for example the distribution of contaminated areas or of the population of radiological refugees — are very asymmetrical, with important distribution tails. The mean is thus notably higher than the median. Favoring the mean rather than the median would lead to over represent extreme cases with respect to their probability and thus suggest a biased picture of the phenomenon[26].

For other costs such as for example costs related to foreseeable reductions in tourism activity, it is not possible in the present state of our knowledge, to rely on a statistical distribution. Such phenomena are unquestionable; they benefit from modeling, but not in the way physical phenomena undoubtedly give rise to a statistical distribution with respect to their main parameters. For this reason, we establish a favorable case and an unfavorable case

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[23] One could illustrate this choice by saying that radiological costs would be borne by France, even when occurring abroad, i.e. that France would compensate affected victims. This is only an illustration which says nothing of hypothetical compensations. The choice thus made considerably simplifies calculations. It seems more legitimate than excluding everything located beyond the borders.

[24] As was observed after the Fukushima accident.

[25] These choices again arise from the need to simplify; the other alternative would mean horrendous complications.

[26] Heavy distribution tails is a phenomenon which should be accounted for, but in the framework of a more ambitious study than the mere estimation of costs representing median accidents.

which allow us to provide both an estimation bracket and to check that the suggested estimate is close to a median value.

4.7. Future progress of research on accident costs

The figures provided here improve upon 2007 estimates, particularly with respect to two important aspects:

- All economic costs have been revised. All are estimated in more detail, backed by more precise arguments, using more explicit methodologies.

  These are applied to scenarios for example those describing reductions in tourism activity. Such scenarios result from a careful study of accumulated knowledge, in the present instance relative to tourism crises in different countries and different areas of the world. Scenarios are based on actual meaningful cases and in no way on exceptional events with no established representativeness. However, IRSN not being a specialist, for example in matters of tourism, it is possible that more detailed studies reveal more appropriate scenarios in the future, for example due to the particular character of tourism in France or to the specifics of a nuclear crisis.

  All economic costs are treated in the same fashion.

- As far as radiological costs are concerned, contaminated areas have been estimated on the basis of simulation runs on three French sites representative of the diversity of the nuclear fleet; these were carried out with the computer chain C3X (see section 5). Other radiological cost are based on computations carried out for the 2007 report.

Future progress is thus envisaged today in essentially three directions:

- confronting the scenarios used for estimating economic costs to the expertise of specialists capable of improving them;
- implementing a PSA3 study up to the best standards;
- studying in detail the contamination of territories.

In addition, indirect costs described above (section 4.2.3) are addressed individually for each type of cost. A more ambitious approach could envisage grouping all direct costs, and studying indirect costs globally in a second stage. The advantage of such an approach would be the possibility to resort to more sophisticated macroeconomic tools, for instance general computable equilibrium models, and to take into account impacts on the financial aspect of the economy.

The sequel of this report is dedicated to describing the methods used to estimate each cost item mentioned (table 3 or Figure 7). Radiological costs are addressed first, economic costs afterwards.

5. MODELING RADIOLOGICAL CONSEQUENCES

As indicated in section 4.4 above, a number of components of the complete cost of a nuclear accident are directly related to radiological consequences of the accident for the people (health risk), for the environment (more or less contaminated territories and natural resources) and for property (particularly agricultural production). Estimating these cost items thus requires an assessment of radiological effects consecutive to the model accidents selected to describe each of the two families of accidents. This assessment requires modeling the atmospheric dispersion of releases and their fallout in the form of surface deposits.

5.1. The computer chain

Preliminary estimations conducted in 2007 used the European code Cosyma (PC Cosyma 1995); this is not adequate to model dispersion over long distances (see appendix 2). Presently, estimates for contaminated areas are based on the IRSN platform C3X; this is an operational computer chain for radiological consequences (atmospheric dispersion, radioactive fallout and doses potentially received by exposed persons) intended to be used in an emergency situation.

This platform relies on two distinct atmospheric dispersion codes:

- a Gaussian model (called pX) intended to calculate dispersion over limited distances (a few dozen kilometers); it is comparable to Cosyma in this respect;
- a Eulerian model (called ldX) dedicated for long distances (several hundreds to thousands of kilometers).

Appendix 3 provides technical details.

Like all Gaussian models, pX is based on the analytic solution of the advection-diffusion equation obtained under simplifying hypotheses (see appendices 2 & 3). This Gaussian solution features standard deviations which model the spread of the plume as a function of time. Classically, their time-evolution is modeled by empirical laws derived from experiments carried in situ. Several such laws exist and are, essentially, taken into account by pX. Such models have the advantage of being fast and able to operate with limited input data. However, contrary to Gaussian model Cosyma, pX is a so-called puff diffusion model. Breaking down the plume into independent puffs makes it possible to provide a fine rendering of the complex kinetics of a release and, more importantly, of a flow which is not homogeneous in space and time. In contrast, plume models such as Cosyma assume homogeneous wind fields which de facto limits their validity. IRSN considers that pX used with a tridimensional wind field is valid up to 80 km from the site, an empirical appreciation.

Eulerian model ldX resolves the advection-diffusion equation on a grid. Such models are frequently used to represent atmospheric pollution, for example relative to road traffic. ldX is a cutting edge code for practical applications[27]. Contrary to Gaussian models, ldX is capable of simulating the dispersion of a pollutant over long

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[27] In a purely scientific framework, unconcerned with applicative considerations, other modelling possibilities exist, notably Lagrangian models. However, theoretical advantages of these models can be limited by practical considerations of representativity. The superiority of one type of model over the other is not established today.

distances, up to the entire globe. However, by its very principle, this type of model provides an average concentration per elemental cell of the grid, which limits its utilization to areas removed from the site of the accident by more than 5 to 10 times the size of a grid cell.

5.2. Climatic data

The rendering of climatic conditions is considerably more detailed in C3X than in Cosyma. As explained above, this is due to the very nature of the modeling approach. Cosyma represents climatic conditions over the entire computation domain by a few parameters pertaining to the site (hourly meteorological data at the site). As every plume model, it shifts the plume mechanically, in one block, hour by hour, in response to changes in the climatic conditions *at the site*.

In contrast, pX models the plume as a fine series of independent puffs which evolve in response to the climatic conditions they encounter as they travel. Meteorological conditions (wind, rain) vary in time and space; they are interpolated from available meteorological data; these are typically provided by the French Meteorological Institute (Météo France) on a 10 km grid and hourly. This approach is much more realistic than in Cosyma and is notably capable of taking into account topography and orography.

On the other hand, Eulerian model ldX features even finer physical models, directly calling on more than 20 advanced meteorological parameters such as relative humidity or height of clouds. The size of its computation grid generally corresponds to that of the meteorological data used as input, for instance, 211 x 141 grid elements of 10 km for a run over France with nine levels on the vertical up to about 3 km in altitude.

6. COSTS RELATED TO CONTAMINATED TERRITORIES

The following sections detail the estimation procedure for the cost items listed in table 3. The aim is essentially to present the main features of the methods adopted. Details will appear in technical notes to be published in the future.

6.1. Two categories of contaminated territories

Contaminated areas are calculated as indicated above and are grouped in two categories depending on the extent of cesium 137 contamination taking as a reference the decisions taken after the Chernobyl accident in Ukraine, Russia and Belarus:

- Exclusion zones, i.e. highly contaminated territories from which populations must leave for many years. In reference to the Chernobyl accident, they corresponded to cesium 137 deposits above 555 kBq/m²[28]. After the Fukushima accident, Japanese authorities based their decisions on dose limits which correspond to very similar levels of activity.
- Other contaminated areas, where cesium 137 deposits are comprised between 37 and 555 kBq/km²[29].

These two categories are each considered globally: a flat cost per square kilometer is applied to corresponding areas resulting in an estimation of the costs of contamination. This approach may be refined in the future.

6.2. Unit costs of exclusion zones

The unit cost adopted in the absence of further detailed studies is 10 M€/km². This round figure — to be refined in the future —, is acceptable since its contribution to the overall cost is minor[30]. Nevertheless, a few elements on this topic can be suggested:

> Two approaches can be considered for this figure: a utilitarian approach which estimates the value of corresponding areas by the sum of revenues they can provide to their residents; and on the other hand, a willingness to pay approach which estimates how much the people are ready to pay to avoid having one square kilometer of their territory becoming an exclusion zone.
>
> A utilitarian approach for rural areas can rely on the value of agricultural production; this leads to a value of 5.6 M€/km²[31]. The value of a territory being greater than its sole agricultural value, a figure of 10 M€/km² does not seem absurd[32]. In a willingness to pay approach, one could call upon estimates produced by health economists[33]; a

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[28] 15 Curies/km², the previous unit for activity which was used by the soviet authorities.

[29] That is to say between 1 Curie/km² and 15 Curies/km².

[30] No effect on the severe accident for which exclusion zones are of negligible extent as a first approximation; about 3% for the major accident (see table 5 of section 6.4 hereafter).

[31] French agricultural value added amounts to about €72b for an agricultural area of 32 million hectares; this leads to an annual mean value of 2,250 €/ha. Summarily discounting at 4% (social discount rate) results in a value of 5.6 M€/km².

[32] A value of €1m per km² must be rejected if one wants to remain representative, as well as a value of €100m km².

value of 10 M€/km² would then be equivalent to the loss of eight life years in rural areas[34] which again appears acceptable as a first approximation.

6.3. Unit costs of other contaminated territories

Unit costs of other contaminated territories amount to 5.23 M€/km²; this is based on experience of the management of this type of area reported for Belarus[35] which corresponds to the following figures:

Table 4: Euro equivalents of annual public aid in Belarus

Solidarity	2 000 € per ha and per year
Support to agricultural businesses	650 € per ha and year
Environmental cost	375 € per ha and per year

Source: CEPN, Note NTE/06/28

Here are a few comments on these figures which relate to rural areas.

Environmental costs to be envisaged after a nuclear accident particularly relate to the management of contaminated agricultural or forest products — more generally to the management of the environment. It could vary widely with respect to land use. The feedback from Fukushima should make it possible to refine significantly the global figure proposed; it may then appear low during the first few years, but may also turn out high 10 or 20 years after the accident.

Support to agriculture varies widely in France according to the type of agriculture; this has been the case for many years without any nuclear accident occurring. A significant part of direct support originates from Europe's common agricultural policy which amounts to about €10 billion per year for French agriculture, i.e. on average slightly over 300 €/ha[36]. Given this partial indication, the above-mentioned figure does not appear totally unreasonable, at least as long as the concerned areas are not huge.

Solidarity grants form the major part of the unit cost in Belarus; these grants are not all costs, strictly speaking, but largely correspond to transfers just as the diverse solidarity grants existing in France. Corresponding figures provide a first approach (which will need to be refined) of the detriment relative to living in a contaminated territory; it is for this reason that they are used here[37]. This aid corresponds to expenses relative to health such as "clean meals" served twice a week in schools or holidays in non-contaminated areas offered to schoolchildren; bonuses paid out to civilian servants; benefits granted to employees; etc. The unit cost of 2000 €/ha represents

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[33] To avoid wasting public funds in the health sector, i.e. avoid a performance inferior to what could be achieved at the same cost, health economists I provide a monetary equivalent of a life-year saved. Estimates range from 20 000 €/year to 50 000 €/year in various studies (see, for example, Le coût du cancer, Philippe Tessier, http://www.sgoc.fr/DU%20oncogeriatrie/2009-2010/007%20tessier.pdf)

[34] Assuming a life-year at 35 000 € (see previous footnote) and using a rural population density of 35 per km².

[35] A study performed by the CEPN in 2006 to help establish this estimate.

[36] European Common Agricultural Policy in 2009 amounted to 9867 M€ for France with an agricultural area of 32 million hectares.

[37] The same logic leads to use the support to agriculture as a proxy to measure its losses.

about €5700 per person and per year[38]. In the future, this cost item should benefit from being broken down and analyzed in the context of the French post-accidental doctrine.

In total, the unit cost retained is close to 300 000 €/km² per year (3025€/ha in the above table 4). The global amount calculated (5.23 M€/km²) thus corresponds to 17.44 years whereas the lifetime of contaminated zones would evidently be longer. The reduction thus operated is due to a discounting procedure at the rate of 4% over 30 years which calls for an explanation.

Several reasons favor simplifying by leaving unit costs constant over 30 years and neglecting residual costs:

- radioactive decay reduces the pollution from cesium 137 by half in 30 years' time;
- aid, for instance directed to agricultural businesses or to the management of the environment, must have a cumulative effect, improve conditions, and lead to stabilized situations over 30 years;
- finally, it is likely that public support be reduced after a period of 30 years; this would reflect a "social stabilization": those who wished to live elsewhere are gone, those who remain on-site have adapted to the situation…

Is it not illusory to attempt to model finely the diversity of such effects? Is it not, on the contrary, simpler and more transparent to simplify as indicated? In order to refine, it would be necessary to model areas decreasing with time as well as decreasing levels of public financial support. In any case, as a first approximation, brutally adding 30 additional years to the proposed estimate, with the same areas and the same unit costs, and discounting using a decreasing rate of discount would constitute a large overestimation[39].

6.4. The extent of contaminated areas

The extent of contaminated areas has been estimated in 2007 using the Cosyma 1995 code. This code is only valid at short distances from the site and remains, in this range, a rudimentary tool given what is possible to achieve today. However, these estimates offered the advantage of not neglecting an element of cost (see section 4 above, particularly figure 8), of pinpointing the problem in the case of large releases, and of pointing out the need to progress on this question. Estimates relative to the severe accident, where the contamination of territory does not play a crucial role, remain those of Cosyma; on the other hand, the contamination due to major accidents is estimated with the computer chain C3X used at the IRSN crisis center (section 5.1). This is a cutting edge tool; it was used to study three different sites representing the variety of all French sites; for each site, 100 simulations were run based on random drawings from the actual meteorological data of year 2010.

6.4.1. The severe accident

For this accident, exclusion zones are very limited in extent (between zero and 20 km² median values). They are therefore taken equal to zero in the present study. More detailed estimates will be proposed in the course of PSA3 studies which should not modify global cost estimates.

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[38] In rural areas, the average density of population amounts to 35 habitants/km² environ.

[39] It would add about 40% to the proposed cost; this should probably be reduced by more than half, but the costs of the first 30 years should then also be reduced…

Other contaminated territories spread over 2 100 km² (median value). The unit cost mentioned above (5.23 M€/km²) leads to an order of magnitude of €11 billion for the cost of "other contaminated territories". The cost for the first year would be 700 million (on the basis of 0.3 M€/km² per year, see 6.3 above) which appears sustainable for the country's budget, at least for several years.

6.4.2. The major accident

For the major accident, corresponding median areas (see 4.6) are:

- 1,300 km² of exclusion zones; and
- 18,800 km² of other contaminated zones.

This implies a complete estimate of €110 billion as indicated in table 5 below.

Table 5: Cost of contaminated territories for a major accident (billion euros)

Areas withdrawn from production	13	1,300 km² of exclusion zones @10 M€/km²
Other contaminated areas	98	18,800 km² of other contaminated territories
Total (rounded)	110	

7. OFFSITE RADIOLOGICAL COSTS

This cost category includes five items:

- emergency countermeasures;
- health costs (radiological);
- agricultural losses;
- relocation costs;
- psychological costs.

The first three items correspond to the classic "consequences" approach (see 4.1, as well as figure 7 of 4.4).

7.1. The cost of classic consequences

As explained in section 4.1, the most immediate consequences are the health effects of radioactivity, essentially an increase in cancer risk. In order to reduce this risk, emergency countermeasures are in order such as evacuation, confinement and ingestion of stable iodine tablets. They are temporary and their cost is relatively low. Another measure appears very quickly: restrictions on the consumption of contaminated foodstuffs whether this is decreed by the authorities as maximum admissible concentration levels or results from a rejection by society (a boycott initiated by consumers, or possibly due to retailers, or even a ban decided by the producers themselves). The more severe the restriction, the more health costs are reduced. These three components are therefore related and, in practice, their estimation can only be jointly calculated on the basis of a computer code.

The code used here is the European Cosyma code (see 4.1) which was the basis for the results obtained as early as 2007; these provide an order of magnitude for the cost of classic consequences; it can be used for calculating global figures.

For severe accidents, these costs vary between a low estimate of €3.1 billion for the conventional S3 accident (see section 1) which is a lower bound for accidents in this category; and an upper bound of €14.6 billion for the S3D accident intermediate between S3 and S1. A mean figure of €9 billion was retained. This simplification appeared legitimate for at least two reasons:

- Modifications which may result from future detailed estimates will only affect a few percentage points of the total cost[40]; they will not modify the global implications of the figures.
- Detailed estimates need extensive computation capabilities and a refinement in analysis which will require a few additional years of work.

These estimates assume that all contaminated foodstuffs are lost, particularly because of a boycott by consumers[41]; this assumption appeared the most realistic in the case of a severe accident where contamination

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[40] A 50% modification would only result in a 4% difference in global costs; this would not affect global conclusions…

[41] The code uses the concentration beyond which food is lost as a parameter. The minimal figure accepted by Cosyma is 10 Bq/kg, a very low concentration which correctly represents the boycott assumption.

remains limited in extent and in time. As a result, agricultural losses nearly represent the total offsite radiological costs, consumers exercising extreme precaution. Health costs only represent a few percentage points of offsite radiological costs. Consumers give priority to their health and that of their loved ones even at the cost of heavy losses for the agro-industrial sector. This type of social trade-off, which needs to be confirmed and studied in more depth in the future, shows how important are the reactions of society for the management of the crisis. Incidentally, there is a link between social acceptance in France and the extent of image costs which are largely due to a decrease in foreign demand (section 8.1 hereafter).

In case of a major accident, assuming a boycott of contaminated produce appeared excessive because quantities concerned would be much higher (thus making substitution much more difficult), on the one hand, and because the contamination of foodstuffs could last for several years thus allowing explanations provided by specialists to convince at least part of the population. It is assumed that contaminated products would be consumed up to a level of 100 Bq/kg, the concentration limit adopted in Belarus a few years after the Chernobyl accident, as well as in Japan since April 2012.

Given this less stringent rejection of agricultural production by society, offsite radiological costs of major accidents vary between €48.4 billion for the upper bound S1 and €5.9 billion for the intermediate S3D accident considered as the lower bound of the category[42]. The average cost then amounts to €27.1 billion. Again, future modifications resulting from detailed estimates will only affect a few percentage points of the global cost[43]. They will help better understand the variability of these costs within the category of major accidents.

In contrast with the severe accident, health effects significantly contribute towards costs, varying between 9% of health and agricultural costs to more than 40% of these costs.

Table 6: Health and agricultural costs of the severe accident

	S3		S3D		Severe accident	
	Billion euros				(Billion euros)	
Short-term health effects	0		0			
Emergency countermeasures	0		1		**0**	0%
Long-term health effects	0,1	2%	0,5	3%	**0,3**	3%
Agro industrial losses	3	98%	14	96%	**8,5**	96%
Total	3	100%	15	100%	**8,9**	100%

Source: Cosyma, computations conducted for the GP 2007 report, concentration limit 10 Bq/kg, representing a boycott of products, even slightly contaminated, by consumers and by the retail sector. The severe accident is the mean of S3 and S3D.

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[42] The intermediate S3D accident thus features offsite radiological costs of €14.6b with a concentration limit of 10 Bq/kg (section 7.1), but only €5.9b, less than half, for a concentration limit of 100 Bq/kg which is nevertheless stringent according to a number of radio protectionists. Moving from boycott to 100 Bq/kg increases the percentage share of health costs; this is mechanically due to the reduction of the agricultural bill and, to a lesser extent, to ingestion of contaminated foodstuffs below 100 Bq/kg.

[43] A modification of 50% in this figure, however substantial (€26b) would only represent 5% of the total cost of major accidents.

Table 7: Health and agricultural costs of the major accident

	S3D		S1		Major accident	
	Billion euros				(Billion euros)	
Short-term health effects	0		0			
Emergency countermeasures	0		6	13%	**3,1**	11%
Long-term health effects	0,6	9%	20	41%	**10,3**	38%
Agro industrial losses	5	88%	22	46%	**13,8**	51%
Total	6	100%	48	100%	**27,1**	100%

Source: Cosyma, computations conducted for the GP 2007 report, concentration limit of 100 Bq/kg

7.2. Psychological costs

Psychological disorders may arise from dramatic events in a person's life; they can be experienced as disasters, for example being diagnosed with cancer, losing a loved one, etc. Some accident victims can experience in this way the personal upheaval implied by the accident (the need to leave one's land, the loss of employment, separation, etc.). Psychological disorders such as depression, anxiety disorders and posttraumatic stress can then appear. War conditions have triggered the study of these types of disorders, particularly when affecting soldiers returned to civilian life. In general, psychological disorders affect the health of their victims, reduce their capacity and may lead to sick leave; corresponding costs are borne by the person, by the state through its health system and by businesses.

Disasters — whether natural, technological or sociopolitical —, are traumatic events at the collective level: they produce a collective posttraumatic stress which causes a significant increase in psychological disorders — i.e. ailments considered as such by health institutions. Their expression is globally the same as those of disorders not related to a disaster.

Psychological disorders are considered as serious health consequences of catastrophes in general, of the Chernobyl and Fukushima accidents in particular[44]. The cost must thus be estimated whatever the difficulty of the task[45].

The proposed numerical estimate is limited to the most immediate costs, those which would directly affect the economy, i.e. the cost of healthcare extended to victims of psychological disorders, particularly the most seriously affected persons, and corresponding sick leave. Ex-ante, society may be ready to spend more to avoid psychological disorders as is the case for such ailments as cancer. As a first estimate of psychological costs, such a direct approach to the willingness to prevent has been considered too ambitious, open to criticism, as well as difficult to implement in practice. As a starting point, it was deemed preferable to limit the scope of the estimate to direct costs; this first step nevertheless sheds light on a number of unknown features of this question. At a later

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[44] « *A 25 Year Retrospective Review of the psychological consequences of the Chernobyl accident* », E.J. Bromet, J.M. Havenaar, L.T. Guey, 2011, Clinical Oncology n°23, p.297-305; "*Fukushima: Fallout of fear*", Geoff Brumfiel, http://www.nature.com/news/fukushima-fallout-of-fear-1.12194

[45] Not estimating these costs would lead to underestimate the value of prevention (see section 4 above). To our knowledge, the proposed estimate is the first in this field.

stage, the contribution of such costs to the value of preventing corresponding accidents will need to go beyond direct costs.

Estimating the psychological cost requires scenarios depicting the increase in psychological disorders after a nuclear accident; these remain schematic, but reflect existing studies worldwide[46]. These do suggest increases in psychological disorders consecutive to a catastrophe and essentially distinguish between a proximate zone ("epicenter") and a distant zone; psychological effects are naturally more acute in the proximate zone, particularly among relocated persons. In the case of a nuclear accident, compulsory relocation zones seem to provide the most natural definition of a proximate zone. This model implies important variations of psychological costs with respect to accident location and climatic conditions.

Two types of economic consequences are implied by psychological disorders: the cost of healthcare and the cost of corresponding sick leave. The direct cost of healthcare has been estimated on the basis of French studies dedicated to psychological costs after a disaster[47]. The total cost of sick leave includes the cost for the Health Insurance and the direct and indirect costs for businesses[48].

This first estimation exercise shows that psychological costs would not be negligible in case of a *major* accident: between €12 and €22 billion depending on the location of the accident. It is composed of 45% healthcare, essentially (90%) extensive and prolonged treatment; 55% are due to the cost of lost workdays. This breakdown varies dramatically during the course of the 25 years during which losses due to psychological disorders[49] occur: losses related to sick leave represent 75% of the total in the first year but decrease to 25% of this total at the end of the period.

Psychological costs thus represent about 4% of the total cost for the major accident. Therefore, they should be considered by crisis management. In contrast, they would represent less than 1% of the total cost of a severe accident (less than €1 billion). These estimates are based on studies which will be proposed for publication in peer-reviewed journals.

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[46] The prevalence of benign and moderate mental disorders is around 10 %, mean worldwide value, according to the WHO Study on Mental Health Worldwide, 2000 edition. This could double and rise to about 20% after being exposed to a disaster as was the case after the 2004 tsunami in Asia according to the study "*Mental Health Assistance to the Populations Affected by the Tsunami in Asia*" published by WHO (2010). The prevalence of mental disasters would then decrease in the course of time to settle after a few years around 15 % in the areas severely affected by the disaster. Thus in the long run, the excess in psychological disorders could be 5 to 10 points above the initial situation before the disaster.

[47] Studies conducted in France by the InVS after storm Xynthia and by the '*Direction Générale de la Santé*' after the floods of the Somme and those experienced in the Gard area. According to these studies, the direct cost of psychological healthcare in France amounts to € 2,000 per person and per year. The major part relates to the most severe cases which require a prolonged stay in specialized facilities.

[48] The total cost of sick leave in France would amount to some 315 euros per lost workday. Half this cost would be borne by the Health Insurance, the other half by businesses according to a study by Aon Consulting (2008). When multiplied by the annual number of lost workdays, this unit cost provides an estimate of the annual cost of sick leave.

[49] Five years only in the event of a severe accident.

7.3. Relocation costs

Relocation costs arise because it is necessary to provide housing to radiological refugees. Based on the Fukushima experience, three stages must be considered: emergency sheltering which lasts up to a few months at most; temporary housing in temporary shelters such as prefabs; and finally, permanent relocation after 2 to 5 years[50]. Emergency sheltering costs represent less than 5% of total relocation cost. As far as other items are concerned, housing standards comparable to what is observed elsewhere in the world have been assumed for permanent relocation, while temporary sheltering conditions are based on Japanese post-Fukushima standards.

With this knowledge of standards, evaluating relocation costs in France requires unit costs for the three types of housing. These were obtained from housing and construction professionals through private interviews, i.e. unpublished data. The main factor for cost variations turns out to be the construction of water and electricity distribution networks. To reduce relocation costs, one should therefore be careful to relocate refugees as close as possible to existing networks and to build permanent housing, as far as possible, on the sites used for temporary relocation so as not to duplicate the construction of the said distribution networks.

As a result, the cost of relocation is estimated around €100,000 per refugee with an uncertainty bracket of ± 30%. The cost of relocation in case of a severe accident should therefore be lower than €1 billion, whereas it could amount to some €10 billion in median terms in case of a major accident (about 2% of total accident cost). These estimates are based on studies which will be proposed for publication in peer reviewed journals.

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[50] The time span required for the construction sector to resorb excess demand consecutive to the nuclear accident.

8. IMAGE COSTS

Image impacts can be very serious for affected economic entities: think about tourism in Tunisia or Egypt or the sad affair of the "Spanish cucumber" (Europe, 2011). Three image costs are considered here: the impact on safe agricultural produce; the effects on tourism in France; and the effect on other French exports, notably those of the nuclear power sector.

8.1. Agricultural image effect

The idea that lost agricultural productions are limited to those measured above maximum concentration limits would lead to a sizable underestimation of the cost of a nuclear accident. The immediate effect of an image crisis affecting food products is the reduction in demand for the products perceived as risky, including those free of any contamination. Accounting for these losses therefore entails no double counting with those relative to contaminated agricultural productions.

> A recent emblematic example of a food image crisis is that of the "Spanish cucumber". In the course of the 2011 summer, cucumbers produced in Spain were suspected of being contaminated by bacteria possibly causing serious damage to human health, only to be exonerated of this charge afterwards. The suspicion of contamination was enough to stop their consumption. The boycott extended beyond the mere Cucurbitaceae and all Spanish exports of fruits and vegetable plummeted during several weeks. Weekly losses were estimated around €200 million for the Spanish economy. Being the second European producer of cucumber after Spain, and although located several hundreds of kilometers from the suspected site of contamination, the Netherlands also suffered from the crisis with losses estimated around €10 million per week.

In general, as soon as the first case of contamination is known, exports drop by more than 40%, dramatically and suddenly[51]; the return to normal extends over a period of 2 to 3 years. In the meantime, 10% to 20% domestic consumers turn away from the foodstuffs subject to this type of branding and substitute them with other products considered healthier. Feedback from Fukushima is less clear than this general picture[52].

Such percentage reductions in demand essentially concern the food industry, agriculture and food retailers. When applied to the value added by these sectors, they provide an estimate of direct image effects.

Corresponding losses imply indirect effects and induced effects (see 4.2.3) which, globally, are not agricultural and approximately amount to about the same level of losses as agricultural losses themselves.

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[51] These figures are based on the effects in France of crises having affected the meat sector reported in the study « *Les effets sanitaires de la filière viande* » published in 2007 by INSEE (the French Statistical Institute). The food crises considered in France are the foot and mouth disease in 2001 and the bovine spongiform encephalopathy (BSE) in 1996 and 2000. Outside France, the following crises have been examined: the avian flu in 2005, the severe acute respiratory syndrome (SARS) in 2003, the Fukushima accident in 2011.

[52] In Japan, food exports for the first nine months of year 2011 (320 billion yen) are lower by 7 % in value compared to the same period of year 2010 (344 billion yen).

In total, the complete image effect on agricultural products is estimated at €13 billion for a severe accident and €60 billion in case of a major accident[53] which amounts to 10% and 14% of total cost. These estimates are based on studies which will be submitted for publication in peer reviewed journals.

The agricultural dimension thus appears of primary importance for nuclear crisis management and the *image* of concerned productions *does* represent the most critical problem.

Table 8: Agricultural image cost (billion euros)

	Severe accident	Major accident
Direct costs	1	2
Indirect costs	1	2
Induced costs	0	0
Total	**1**	**5**

8.2. Impact on tourism

Crises affecting tourism activity are numerous; they become more and more costly as international tourism develops.

In order to establish scenarios for the reduction in tourist activity after a nuclear accident in France, it has appeared essential to distinguish three components within the French tourist activity: domestic tourism, European tourism and international tourism. Indeed, different tourists tend to behave differently.

- The quality and the level of detail of the information they rely upon strongly depends upon their distance from France. In matters of image, a distant consumer tends to globalize; even if a limited portion of French territory were affected, the distant consumer (American, Chinese, etc.) would nevertheless tend to consider the entire country to be contaminated. In contrast, the French and European tourist has better knowledge of France and is not as easily mistaken.
- The distant tourist faces many more alternative possibilities. Granted, France is unique… but Italy is also a beautiful country and, for a distant tourist, choosing the latter practically implies no additional cost.

The extent of radiological consequences would necessarily influence the reduction in tourism activity; different scenarios have therefore been sought for the severe and the major accident on the basis of more or less acute tourism crises reported through the statistics of the World Tourism Organization[54].

Research on tourism crises indicates that about half of the reduction in tourism activity could be due to European tourists regardless of the type of accident. This result should help managers to reduce corresponding costs.

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[53] These estimates represent sizeable increases over those proposed in 2007. Figures are computed at the date of the accident.

[54] http://www2.unwto.org/fr

In total, the complete impact of the reduction in tourism is estimated at €25 billion in case of a severe accident and €75 billion for a major accident, these figures being calculated at the date of the accident. The order of magnitude of this image effect is therefore slightly below 20% of total accident cost. It is larger than the agricultural image effect. Needless to say, it deserves full attention from crisis management. These estimates are based on studies which will be proposed for publication in peer-reviewed journals.

Table 9: Tourism image cost (billion euros)

	Severe accident	Major accident
Direct costs	13	36
Domestic tourism	*2*	*5*
European tourism	*7*	*17*
International tourism	*4*	*14*
Indirect costs	9	28
Induced costs	3	11
Total cost	25	75

8.3. Industrial image effect

Effects on industry in general are distinguished from effects on the nuclear power industry.

An order of magnitude for the former has been sought on the basis of the Japanese experience. The March 11, 2011 disaster caused a sudden reduction in final demand for manufactured products in Japan (both national and foreign); this was followed by a rapid return to normal, less than one year after the catastrophe[55]. Mechanically duplicating the Fukushima experience would imply a reduction in demand for industrial products of 25% immediately after a major accident and a relatively rapid return to normal within 3 to 6 months. However, French industry carries less weight than the Japanese[56]. Besides, accidents considered here should logically have less impact than a combined natural disaster and nuclear accident as was the case in Japan. For this reason, the reduction consecutive to a nuclear accident in France has been considered lower, at about 10%; however, it would affect the French economy for a longer time period, between 6 to 24 months after the accident; indeed, it would not benefit from the economic stimulus resulting from the cleanup of debris and the re-construction effort required by the earthquake and tsunami in Japan.

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[55] Statistics from the METI (Ministry for Economy, Commerce and Industry).

[56] Industry represents 14 % of French GDP in 2011 compared to 27 % for Japan in 2010.

As far as the French nuclear power sector is concerned, it would first and foremost be affected by worldwide demand. IAEA conducts regular prospective studies. These reflect a reduction of the share of nuclear power in worldwide electricity production after Fukushima[57]. The shortfall related to the Fukushima accident is thus estimated around 20% of world nuclear production in 2030. Such studies provide a first approach to estimated losses for French exports: a reduction of 20% following a major accident (and four times less after a severe accident). One could argue that the market share of France could also be affected; this, however, would be more theoretical than practical, because most French nuclear exports are composed of long-term contracts relative to nuclear fuel and maintenance of existing reactors.

These are the direct losses due to the reduction in demand; they produce indirect effects and induced effects which approximately amount to the value of direct losses. The table below summarizes corresponding costs.

Table 10: Industrial image cost (billion euros)

	Severe accident	Major accident
Direct costs	6	22
Excluding nuclear power	*3*	*11*
Nuclear power	*3*	*10*
Indirect costs	5	19
Induced costs	1	5
Total cost	12	46

With these assumptions, the industrial image cost is estimated at €12 billion for a severe accident and €46 billion in case of a major accident; about 45% is relative to exports of the nuclear power sector. The importance of this image cost is therefore non-negligible, amounting to about 10% of the total cost of the accident.

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[57] *Energy, Electricity and Nuclear Power Estimates for the Period up to 2050,* AIEA, 2010 Edition and 2012 Edition

9. IMPACT ON THE COST OF ELECTRICITY PRODUCTION

Worldwide experience shows that a nuclear accident causes modifications in energy policies. The Fukushima accident has thus accelerated the exit from nuclear power in Germany; previously, the Chernobyl accident had brutally put an end to Italian projects in this area[58]. While civilian nuclear has not been banned in the East after the Chernobyl accident — other days other ways —, the Japanese situation is quite critical. Three years after the accident, practically all nuclear sites in the country had stopped producing and the cost of the situation was estimated at some $30 billion *per year*[59]. This clearly says how important this component is for the country while no one knows for how long this standstill will last despite efforts by the government to put an end to it.

It is therefore essential to produce an order of magnitude for this cost component — which is often called the "fleet effect", referring to the impact of a nuclear accident in France on the French fleet of nuclear reactors. It is therefore necessary to establish scenarios describing the changes which might affect the French reactor fleet after a nuclear accident: end of nuclear? Status quo?

An intermediate path between these two extremes seems more likely:

- doing nothing, openly or more or less covertly? This seems impossible given the present state of affairs, even if in other circumstances, comparable for instance to the oil shock of the 1970s or even more dramatic, the political world could decide to "do nothing". This scenario would require further examination because "doing nothing" would nevertheless imply numerous adjustments, revisions, controls and reactor shutdowns — all of which would be costly.
- closing down French nuclear sites as early as possible? Stopping nuclear production seems even more unrealistic than doing nothing, but one could perhaps imagine circumstances, improbable today and certainly extremely unfavorable, under which the politically world would decide to terminate nuclear electricity production in France as fast as possible. Such a scenario would also necessitate further study because delays implied in providing replacement solutions and the host of repercussions it would entail are not simple to figure out.

This section addresses the estimation of the fleet effect — which is indispensable given the size of the corresponding costs. It also addresses on-site costs, essentially because the computations required are of the same type for the cost of replacing electricity production forgone on-site.

9.1. Effect of a major accident on the French fleet of reactors

In a context where a possible life extension of French reactors is under discussion, the adopted scenario considers a kind of "moving 10 year reduction" of the lifetime of nuclear reactors constituting the present French fleet. The most serious difficult may not consist in a time schedule of shutdowns — which can be broken down, rendered

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[58] The Caorso nuclear site was brought to a sudden halt *sine die* and the work ongoing on the Montalto di Castro site was closed down following a referendum in 1987.

[59] World Nuclear News, 22 February 2013, *Shikoku joins rate hickers*. It refers to the excess cost of imports of fossil fuels in 2012: 3,000 billion yen (estimate by the Japanese authorities).

more realistic and refined in many ways — but in estimating the production the nation would thus renounce to. In other words: what would have happened without any accident? Would all reactors have seen their lifetime extended for 20 years as requested by EDF thus extending their lifetime from 40 to 60 years? Or should one be even more ambitious and consider, as the Americans do, that it is possible to extend the lifetime of reactors up to 80 years (which would increase the weight of the fleet effect because the accident would imply higher losses of production)? Or should one consider, in the absence of any accident, a scenario where the share of nuclear in French electricity production is reduced in line with the policy considered in 2013 (this would, on the contrary, reduce the cost of the fleet effect)?

The practice of safety discussions has suggested a realistic scheme. In France, the nuclear fleet is subject to in-depth “decennial visits” which constitute, for each reactor, an essential prerequisite for the pursuit — or not —, of its activity for a further 10 year period. This feature has been the basis for the proposed scenario: in the absence of accident the lifetime of reactors is extended by blocks of 10 years. But in case of a *major* accident, authorities reconsider the previous decision to prolong in principle the lifetime by 10 years. A number of reactors are not directly affected; they had experienced their lifetime being extended by 10 years, at least in principle, less than 10 years back; this is now revised; they fall back to the status quo ante[60]. But a few reactors have already been in production for longer than the revised reactor lifetime. In the scenario calculated here, these reactors are immediately shut down which probably overestimates the corresponding costs.

The scenario then features the replacement of the forgone nuclear capacity by a mix of CCGT[61] gas turbines and renewable energies which moves in time towards more renewables as these become more competitive. A unit replacement cost is thus estimated and applied to the structure of the French fleet of reactors resulting in a total replacement cost. This is schematic because very large capacities must be installed within reduced time periods[62].

In this simplified vision, the cost is nil at the end of the lifetime of the fleet which probably underestimates the costs; except if the replacement of the fleet at the end of its lifetime was planned, before any accident occurred, to take place by means of production entirely nonnuclear or at least sufficiently safe for the accident not to have any effect on their commissioning.

This scenario raises a number of other questions, notably relative to the greenhouse effect, to safety of supplies, to safety modifications and to effects in the very long term — and these have not been addressed[63]. Nevertheless, it offers a first vision of the effects of a nuclear accident on the French fleet of reactors and provides a quantification between €116 billion for an accident in 2010 and a zero cost in 2040[64]. Indeed, the size of the fleet effect is directly related to the number of reactors existing at the date of the accident. The mean value of the

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[60] In a general context which would probably be extremely delicate, with notably reinforced controls, etc.

[61] Combined Cycle Gas Turbine, today the most competitive alternative.

[62] Today, due to the immense construction effort which took place in France in the 1970s and 1980s, a mechanical renewal of reactors at the end of their lifetime would be confronted with a quite stiff “cliff effect”.

[63] In addition, estimates assume constant electricity demand and constant nuclear production; alternative scenarios are the object of endless controversies.

[64] Commissioning date of the last reactor of the 2013 fleet plus 40 years. The life extension of French reactors is not enacted; it would increase the value of the fleet effect.

cost discounted to the date of the accident then amounts to €88 billion. This value is close to that for an accident occurring in 2025.

It represents 20% of the total cost of the model major accident. It is therefore essential that crisis managers be concerned with this aspect, address it in the most rational fashion possible and strive to reduce its costs for the nation.

9.2. Fleet effect after a severe accident

The above scenario seems plausible in the context of a major accident with widespread land contamination and, in all probability, profound political and social transitions. In the case of a severe accident, radiological consequences being more limited, industrial constraints should be more prominent in decisions about the future of energy. In particular, commissioning the required electricity production capacities in replacement for nuclear could prove difficult and reduce the rhythm and extent of these replacements. A reduced rate of replacement would, in addition, allow smoothing out the age composition of the fleet of reactors. The French fleet has been constructed at a very sustained pace, a particular feature which requires replacing sizable production capacities in very few years if one adopts a uniform replacement rule; this cliff effect reduces the flexibility of the national electricity production system.

I the absence of a scenario with a “simple” structure, comparable the previous one, the above figure was simply divided by half leading to a proposed estimate of €44 billion. Doing so, the weight of this component rises from 20% to 37% of the total cost meaning that the stakes appear more pressing than in the case of a major accident, at least in relative terms. This phenomenon reinforces the likelihood of a marked reduction of the fleet effect compared to the scenario adopted for the major accident[65].

9.3 On-site costs

Three cost items have been identified as constituting economic costs on the site of the accident: decontamination and decommissioning costs; the cost implied in replacing the electricity not produced on-site because of the accident; and other costs.

In any case, the reactor which caused the accident is lost. In case of a severe accident with more or less controlled releases, other reactors are stopped for several years before being started again as was the case after the Three Mile Island accident. The damaged reactor is decontaminated immediately after the accident. Afterwards, it enters a phase of monitoring before being eventually deconstructed simultaneously with other site reactors at the end of the lifetime of the site.

In case of a major accident, the site is entirely closed and decontamination and decommissioning operations can start immediately.

In both cases, the cost of decontamination and decommissioning is the discounted excess cost of these operations compared to a situation without accident. It is composed up to 75% by decontamination costs and is estimated at

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[65] The lesser weight of the fleet effect in the event of a major accident essentially reflects the higher share of other challenges because of the heavy radiological cost component.

€4.8 billion in case of a severe accident and at €5.4 billion in case of a major accident. These estimates are based on feedback from Three Mile Island — which could be underestimated. Data which will come from Fukushima will be of great interest, particularly unit costs of specific operations; aggregate figures should turn out significantly higher than in Three Mile Island due to the wreckage caused by the strength of the tsunami, because four reactors are affected and because explosions have occurred. Such scenarios are excluded from the present study which only addresses the case of an accident affecting only one reactor. The global figures from Fukushima will thus have to be used with caution.

The cost of the replacement electricity corresponds to the value of the lost reactor, on the one hand, to which is added the cost of temporary shutdown of other reactors on site. In case of a severe accident, these replacement costs are estimated at €5.6 billion at the date of the accident using the same methods as for the fleet effect (again the replacement is carried out by a mix of CCGT gas turbines and renewable energy according to the same modalities and at the same prices as for the calculation of the fleet effect). This figure rises to €9.3 billion for the major accident with the complete loss of the other reactors on site.

Finally other on-site costs include residual maintenance and the monetary value of doses on-site personnel might be exposed to. These costs are negligible compared to other on-site costs.

In total, the proposed estimate of on-site costs at the date of the accident amounts to €10 billion for the severe accident and €15 billion for the major accident.

10. SYNTHESIS OF RESULTS AND PROSPECTS

10.1. Synthesis of results

The outcome of the estimation of the 14 items detailed above is the following:

Table 11: Estimation of accident costs in France (billion euros)

		Severe accident	Major accident
On-site costs	Rehabilitation	5	5
	Replacement	6	9
	Other on-site costs	ε	ε
	TOTAL	**10**	**15**
Contaminated territories	Exclusion zones	ε	13
	Radiological control zones	11	98
	TOTAL (rounded)	**11**	**110**
Offsite radiological costs	Emergency countermeasures	ε	3
	Health effects	ε	10
	Psychological effects	0	17
	Agricultural losses	9	14
	Relocation cost	0	10
	TOTAL	**9**	**54**
Image costs	Reduction in demand for French agricultural products	13	60
	Reduction in tourism demand	25	75
	Reduction in other exports	12	46
	TOTAL (rounded)	**50**	**180**
Effects on the electricity production system		**44**	**88**
TOTAL (rounded)		**120**	**450**

ε means a cost which low, but only from a relative point of view: lower than €1 billion

Accidents are taken as models of their families (see section 3.3); their estimates aim at being median (see 4.6). The above figures are globally identical to those published in 2012, differences being due to work conducted since which does not modify the conclusions to which they point, namely:

1. A major accident profoundly differs from a severe accident

- severe accidents lead to a crisis which is globally of economic nature, a great part of costs being borne by the entire population;
- in contrast, major accidents would lead to massive radiological consequences, the number of victims being potentially high and all kinds of population being potentially affected.

2. This information is of interest for crisis managers

- they help elaborate a global vision of nuclear crises; they thus contribute to avoiding, in the early hours of the crisis, mistakes which could be extremely costly in the long run;
- they help prepare crisis management by showing that radiological consequences are only part of anticipated difficulties, sometimes a minor part of costs; they suggest extending preparation to address the other foreseeable cost items;
- they open up the possibility of working on the reduction of these costs.

3. This information is of interest for safety

- extreme accident cases face the nation with very high stakes;
- consequently, their lower probability does not necessarily compensate for their potential for disaster…

10.2. Prospects

Before moving on to actual prospects, such estimates require a few words of caution:

- The proposed estimates describe the phenomena under consideration. Studying extreme cases would be more demanding and this is the reason why it is not addressed at this stage. For illustrative purposes only, studies suggest that the variable severity of releases within each of the two families (variable source terms) is likely to imply costs varying in the order of -50% to +100%. Overall costs, *otherwise median*, could thus vary within the family of severe accidents between €50 and €250 billion; within the family of major accidents, the median could vary between €200 and €1,000 billion.
- One should keep in mind that the probabilities of such accidents are very low. Focusing attention on nuclear accidents, in fairly great detail as this report does, bestows upon them a reality which can blur the initial assumption i.e. that a radioactive release has occurred on the French soil — which remains unlikely. Many persons, on electricity production sites and within control authorities specifically dedicate all their efforts to avoid such accidents. The above estimates can only reinforce their dedication and their legitimacy.

Beyond the possible avenues for progress described at section 4.7, prospects which can be envisaged today for improving this type of work are, in the order of the above-mentioned cost items:

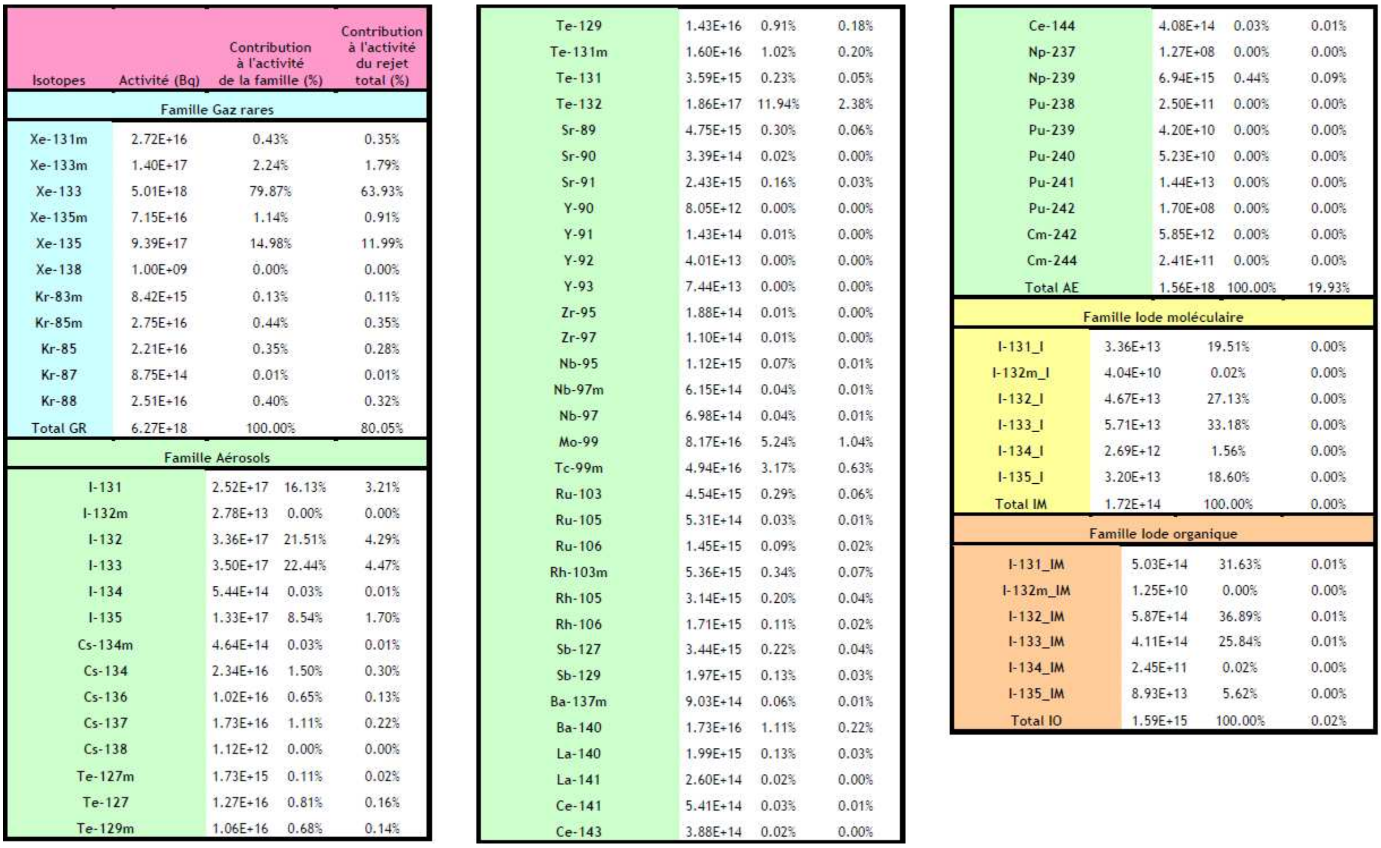
- on-site costs should benefit from lessons learned at the Fukushima decommissioning site. It is possible that the proposed estimates, based on figures arising from the Three Mile Island experience, turn out somewhat optimistic;
- the cost of contaminated territories should benefit from further studies of the unit costs per square kilometer of contaminated territories; in particular, specific studies should detail the effects on specific economic activities of given territories as well as collateral effects on neighboring uncontaminated territories;
- off-site radiological costs should, in the future be based on detailed PSA3 studies;
- image costs could benefit from specific studies conducted outside IRSN which would lead to more precise scenarios of the image impacts on one hand; and on the other hand, it would be desirable to conduct macroeconomic studies of indirect effects. Instead of addressing these item by item, they could thus be studied globally at the level of the country which is expected to give better results. Financial impacts could be included.

Such studies should provide a more detailed understanding of the corresponding phenomena thus moving beyond the global pictures provided in this report.

Appendix 1. The DCH accident scenario

The DCH accident scenario corresponds to a station blackout leading to a core melt. This occurs six hours after the initiator; fission products are released inside the confinement until the vessel ruptures, about 11 hours after the initiator. Up to this moment the confinement is considered intact and leaks from the confinement are normal (extremely limited). However, because of the loss of electricity supply, water sprinklers are unavailable inside the confinement and air circulation systems are at a halt in auxiliary buildings. In this scenario, the vessel is insufficiently depressurized when it ruptures; part of the melt fuel (corium) is thus projected into the confinement in the form of particles; this subjects the confinement to a very high pressure, beyond the design pressure. This very improbable situation is called "*direct containment heating*" (DCH). It is assumed that this phenomenon causes a breach in the confinement; its representative section is taken equal to 27.5 cm². The end of the release occurs after 30 days.

Table A1.1: Synthesis of rejected activities by isotope and by family



Isotopes	Activité (Bq)	Contribution à l'activité de la famille (%)	Contribution à l'activité du rejet total (%)
Famille Gaz rares			
Xe-131m	2.72E+16	0.43%	0.35%
Xe-133m	1.40E+17	2.24%	1.79%
Xe-133	5.01E+18	79.87%	63.93%
Xe-135m	7.15E+16	1.14%	0.91%
Xe-135	9.39E+17	14.98%	11.99%
Xe-138	1.00E+09	0.00%	0.00%
Kr-83m	8.42E+15	0.13%	0.11%
Kr-85m	2.75E+16	0.44%	0.35%
Kr-85	2.21E+16	0.35%	0.28%
Kr-87	8.75E+14	0.01%	0.01%
Kr-88	2.51E+16	0.40%	0.32%
Total GR	6.27E+18	100.00%	80.05%
Famille Aérosols			
I-131	2.52E+17	16.13%	3.21%
I-132m	2.78E+13	0.00%	0.00%
I-132	3.36E+17	21.51%	4.29%
I-133	3.50E+17	22.44%	4.47%
I-134	5.44E+14	0.03%	0.01%
I-135	1.33E+17	8.54%	1.70%
Cs-134m	4.64E+14	0.03%	0.01%
Cs-134	2.34E+16	1.50%	0.30%
Cs-136	1.02E+16	0.65%	0.13%
Cs-137	1.73E+16	1.11%	0.22%
Cs-138	1.12E+12	0.00%	0.00%
Te-127m	1.73E+15	0.11%	0.02%
Te-127	1.27E+16	0.81%	0.16%
Te-129m	1.06E+16	0.68%	0.14%
Te-129	1.43E+16	0.91%	0.18%
Te-131m	1.60E+16	1.02%	0.20%
Te-131	3.59E+15	0.23%	0.05%
Te-132	1.86E+17	11.94%	2.38%
Sr-89	4.75E+15	0.30%	0.06%
Sr-90	3.39E+14	0.02%	0.00%
Sr-91	2.43E+15	0.16%	0.03%
Y-90	8.05E+12	0.00%	0.00%
Y-91	1.43E+14	0.01%	0.00%
Y-92	4.01E+13	0.00%	0.00%
Y-93	7.44E+13	0.00%	0.00%
Zr-95	1.88E+14	0.01%	0.00%
Zr-97	1.10E+14	0.01%	0.00%
Nb-95	1.12E+15	0.07%	0.01%
Nb-97m	6.15E+14	0.04%	0.01%
Nb-97	6.98E+14	0.04%	0.01%
Mo-99	8.17E+16	5.24%	1.04%
Tc-99m	4.94E+16	3.17%	0.63%
Ru-103	4.54E+15	0.29%	0.06%
Ru-105	5.31E+14	0.03%	0.01%
Ru-106	1.45E+15	0.09%	0.02%
Rh-103m	5.36E+15	0.34%	0.07%
Rh-105	3.14E+15	0.20%	0.04%
Rh-106	1.71E+15	0.11%	0.02%
Sb-127	3.44E+15	0.22%	0.04%
Sb-129	1.97E+15	0.13%	0.03%
Ba-137m	9.03E+14	0.06%	0.01%
Ba-140	1.73E+16	1.11%	0.22%
La-140	1.99E+15	0.13%	0.03%
La-141	2.60E+14	0.02%	0.00%
Ce-141	5.41E+14	0.03%	0.01%
Ce-143	3.88E+14	0.02%	0.00%
Ce-144	4.08E+14	0.03%	0.01%
Np-237	1.27E+08	0.00%	0.00%
Np-239	6.94E+15	0.44%	0.09%
Pu-238	2.50E+11	0.00%	0.00%
Pu-239	4.20E+10	0.00%	0.00%
Pu-240	5.23E+10	0.00%	0.00%
Pu-241	1.44E+13	0.00%	0.00%
Pu-242	1.70E+08	0.00%	0.00%
Cm-242	5.85E+12	0.00%	0.00%
Cm-244	2.41E+11	0.00%	0.00%
Total AE	1.56E+18	100.00%	19.93%
Famille Iode moléculaire			
I-131_I	3.36E+13	19.51%	0.00%
I-132m_I	4.04E+10	0.02%	0.00%
I-132_I	4.67E+13	27.13%	0.00%
I-133_I	5.71E+13	33.18%	0.00%
I-134_I	2.69E+12	1.56%	0.00%
I-135_I	3.20E+13	18.60%	0.00%
Total IM	1.72E+14	100.00%	0.00%
Famille Iode organique			
I-131_IM	5.03E+14	31.63%	0.01%
I-132m_IM	1.25E+10	0.00%	0.00%
I-132_IM	5.87E+14	36.89%	0.01%
I-133_IM	4.11E+14	25.84%	0.01%
I-134_IM	2.45E+11	0.02%	0.00%
I-135_IM	8.93E+13	5.62%	0.00%
Total IO	1.59E+15	100.00%	0.02%

Appendix 2. The Cosyma dispersion model

The description below figures in: EURATOM 18822, Probabilistic accident consequence uncertainty assessment using Cosyma, Uncertainty from the Atmospheric dispersion and deposition module.

Atmospheric dispersion is modelled in COSYMA using a version of the Gaussian plume dispersion model, modified to allow for hourly changes in atmospheric conditions such as wind speed and direction, diffusion category and precipitation rate. The model assumes that the concentration distribution within the plume of material is Gaussian both vertically and horizontally at right angles to the mean wind direction.

The basic equation of the Gaussian plume dispersion model is

$$C(x,y,z) = \frac{Q_0}{2\pi\sigma_y\sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) [\exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right)]$$

Where

C(x,y,z) is the time integrated concentration at *(x,y,z)* [Bq s/m^3],
$Q_0$is the initial quantity of contaminant released [Bq],
u is the (constant) windspeed (always in x direction) [m/s],
H is the height of the release [m]

and$\sigma_y$and $\sigma_z$are the lateral and vertical plume spread, respectively [m].

$$\sigma_y = p_y x^{q_y} \qquad \sigma_z = p_z x^{q_z}$$

The standard deviation of the Gaussian distributions (σ_y and σ_z) are described in COSYMA using power law functions.

For one set of atmospheric conditions, the target variables of the Gaussian plume dispersion model are p_y, q_y, p_z, q_z. COSYMA considers dispersion in the six atmospheric stability categories proposed by Pasquill, and designated A to F. Therefore 24 target variables were identified for the atmospheric dispersion model, namely the parameters p_y, q_y, p_z, $q_z$in each of the 6 stability categories. This was subsequently reduced to 16 target variables, as explained in Section 2.7.

The calculations consider both dry and wet deposition to the ground.

Dry deposition is calculated using the deposition velocity, where the deposition rate is the product of the air concentration at ground level and the deposition velocity. The calculated air concentration is modified to allow for the effect of plume depletion during its travel, using the source depletion model. The deposition velocities for three forms of released material, namely aerosols, elemental iodine and organic iodine were considered to be uncertain in this study. It was assumed that all material released in particulate form has the same deposition velocity. The deposition velocity for noble gases was assumed to be zero, with no uncertainty.

Dry deposition to skin was also considered, with different values of the deposition velocity to skin for the three types of material identified above.

Wet deposition is calculated using the out coefficient, Λ, the fraction of dispersing material deposited by rain in unit time. The washout coefficient is related to the rainfall rate, R, by

$$\Lambda = a\,R^{b}$$

so the target variables are the quantities a and b. As with dry deposition, different values of these parameters are used for material released as aerosols, elemental iodine and organic iodine. It was assumed that all particulate material has the same values for these parameters. It was assumed that noble gases do not deposit.

Therefore 12 target variables were identified for the deposition model, namely the deposition velocities to ground and skin and the parameters of the expression for washout coefficient for each of three types of material.

Appendix 3. The C3X platform

The ldX model[66]

ldX originates from a chemistry transport model adapted for IRSN purposes. Such models are used to address a number of environmental questions at the global scale (climate change, stratospheric ozone layer hole) or at a regional scale (cross boundary pollution, large-scale industrial accidents, quality of urban air). They have played a fundamental role since the 1980s as a basis for scientific and technical expertise in the context of atmospheric pollution (for example, for understanding the hole in the ozone layer). For instance, the model EMEP[67] was used by the European Union as a decision making support in the context of country level emission limits for a large number of pollutants (directive NEC, National Emissions Ceiling, 2001/81/EC).

The dispersion of pollutants into the atmosphere, at all spatial scales, mainly depends on meteorological conditions. It results from two major phenomena acting simultaneously: transportation by wind, or advection, which carries the pollutant and affects the direction and dispersion of the plume; and turbulent diffusion which mixes the pollutant with the surrounding air in a chaotic fashion. A large number of exchanges take place at different scales; at the local scale, close to the source, effects related to the release itself and to neighboring obstacles dominate; at the regional scale, the effects of topography play a major role; beyond, at the continental scale, extending over several hundred to several thousand kilometers, the transport of pollutants is mainly influenced by large-scale atmospheric dynamics (depression, anticyclone, etc.). ldX is particularly suitable to model flows at regional and continental scales.

ldX considers chemical species in gaseous phase or in the form of aerosols (matter condensed in the atmosphere); it aims at modeling their interactions and how they may transform under the action of different processes in the atmosphere. Pollutants rejected in the air are horizontally transported over long distances by large-scale air movements and are dispersed under the action of turbulences which mix them with clean air. The period for which they remain in the atmosphere is essentially determined by deposit processes, whether humid or dry. ldX describes atmospheric dispersion in the three dimensions of space under a non-stationary regime. Being Eulerian, it considers elementary volumes of space through which it models the flow of matter; in other words, the atmosphere is discretized and the equations of fluid mechanics are solved for each elemental volume. This allows integrating complex flow conditions, such as obstacles or significant topography, and obtaining a refined analysis of dispersion in time. At each time step, ldX calculates activity concentrations over the predefined tridimensional grid. This type of modeling provides a natural rendering of complex meteorological fields such as provided by weather forecast models.

So-called “dry” deposits result from the interaction between products released into the atmosphere and the ground; they are addressed through the notion of deposition velocity. On the other hand, so-called “humid” deposits only result from scavenging of the released products by rain; they are calculated mainly based on the

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[66] Extraits de Quélo et al., Validation of the Polyphemus platform on the ETEX, Chernobyl and Algeciras cases, Atmospheric Environment, Volume 41, Issue 26, August 2007, Pages 5300–5315

[67] Kevin Barrett and Erik Berge, July 1996. Transboundary air pollution in Europe. EMEP/MSC-W Report 1/96

intensity of rain. Turbulence is addressed by a turbulent diffusion coefficient appearing in conservation equations solved by the model. Lastly, filiation and radioactive decay phenomena are taken into account in the same fashion as in pX.

In order to conduct a simulation, ldX requires the following input:

- data describing the different products released (decay and filiation of concerned radio elements, dry deposition velocity, scavenging coefficients of particles, etc.);
- data describing the release: its location, its composition, the quantities of released products as a function of time;
- tridimensional meteorological data (wind speed and direction, temperature, rain, height of clouds, etc.) as a function of time.

On the basis of this input data (and of a number of other parameters such as the space-time grid, and numerous physical and/or numerical values), ldX calculates instantaneous activities in the air and deposits on the elemental areas of the grid.

The pX model[68]

1. General presentation of the model

Modeling turbulent dispersion of matter by Gaussian puffs addresses the transportation of pollutants in the atmosphere in a simplified fashion. The approach is well adapted for operational uses because computation times are short and required input data fairly simple.

1.1 Analytic solution of the advection-diffusion equation

The theoretical foundation of the method is the advection-diffusion equation for an instantaneous release from a point source. The principle of conservation of a scalar quantity allows expressing the instantaneous concentration c of this quantity through the advection-diffusion equation:

$$\frac{\partial c}{\partial t} + u\nabla c = D\Delta c + S \qquad (1.1)$$

where u is the instantaneous speed, D the molecular diffusion coefficient and S the source term. The Reynolds decomposition into mean and fluctuating values provides the advection-diffusion equation for the average concentration C:

$$\frac{\partial C}{\partial t} + U\nabla C = D\Delta C - \nabla\overline{u'c'} + S \qquad (1.2)$$

This equation is difficult to solve in the general case involving any given turbulent flow. But a few simplifying assumptions make it possible to derive an analytic solution. It is thus supposed that:

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[68] Abstracts from : Soulhac, L. et Didier, D. (2008). Projet pX, note de principe pX 1.0. Note technique IRSN/DEI/SESUC/08-39

- the turbulent flow $\overline{u'c'}$ can be expressed using the gradient of average concentration as $-K\nabla C$, where K is the tensor of turbulent diffusivity;
- the tensor of turbulent diffusivity is diagonal;
- molecular diffusivity D is negligible compared to turbulent diffusivities K_i;
- there is no mean flow;
- turbulent diffusivities K_i are uniform and constant.

The distribution of concentration induced by an instantaneous release (at instant t_0) of a mass Q of pollutant issued from one point (with coordinates x_0, y_0, z_0) is then given by the Gaussian relation:

$$C = \frac{Q}{8\left[\pi(t-t_0)\right]^{3/2}\sqrt{K_x K_y K_z}} \exp\left[-\frac{1}{4(t-t_0)}\left(\frac{(x-x_0)^2}{K_x}+\frac{(y-y_0)^2}{K_y}+\frac{(z-z_0)^2}{K_z}\right)\right] \tag{1.3}$$

From the solution of this equation, it is possible to express the time evolution of the standard deviations σ_i of the distribution of concentration:

$$\sigma_i = \sqrt{2K_i\left(t-t_0\right)} \tag{1.4}$$

It has been known for a long time (Taylor, 1921) that the previous result only gives a good approximation of reality for sizable diffusion periods. Indeed, in the neighborhood of the source, the assumption of a constant turbulent diffusivity is not applicable because the dimension of the puffs has a filtering effect on the spectrum of turbulent energy. The only eddies to contribute to the diffusion of the puff are those with sizes smaller than the dimension of the puff whereas eddies of larger sizes cause a displacement of the center of mass of this puff. As a result, in the neighborhood of the source, the standard deviations σ_i increase proportionally to $\left(t-t_0\right)$.

In order to move forward without perfect knowledge of the time evolution of the standard deviations σ_i, it is possible to reformulate equation 1.3 to make them appear explicitly:

$$C = \frac{Q}{\left[2\pi\right]^{3/2}\sigma_x\sigma_y\sigma_z} \exp\left[-\frac{1}{2}\left(\frac{(x-x_0)^2}{\sigma_x^2}+\frac{(y-y_0)^2}{\sigma_y^2}+\frac{(z-z_0)^2}{\sigma_z^2}\right)\right] \tag{1.5}$$

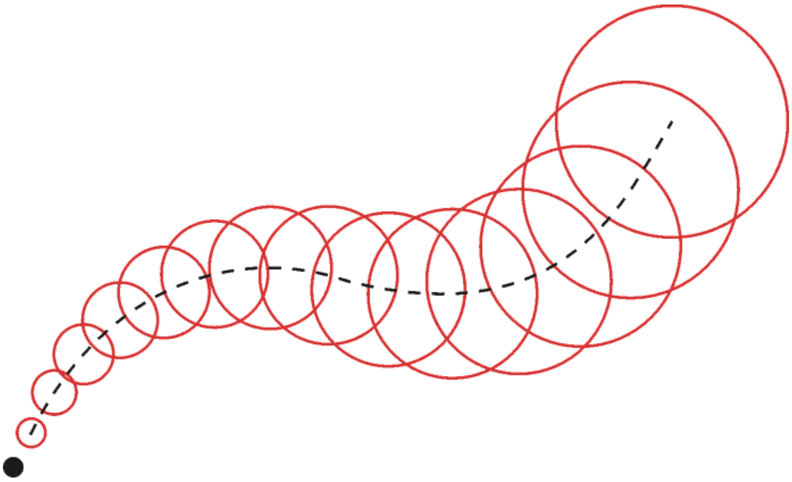
Even if the theoretical assumptions supporting this relation are not generally verified, it has been experimentally observed that the previous equation describes the behavior of a puff of pollutant reasonably well. However, to compute the standard deviations during the course of the growth of the puff, an adequate parameterization is necessary.

In practice, a great number of phenomena control the growth of the standard deviations σ_i as the puff of pollutant diffuses in the atmosphere. Many parameterizations have been developed in the past, empirical or theoretical. They are more or less complex and generally all depend upon the degree of thermal stratification of the atmosphere. In pX, the user can choose between several parameterizations: the Doury model, the Briggs model, the Pasquill model or else a definition of the coefficients for turbulent diffusivity.

1.2 Dispersion models with Gaussian puffs

In an actual situation, meteorological conditions and quantities of pollutant frequently vary in the course of time. The simple solution of equation 1.5 is not adequate to describe the dispersion of pollutants in such a situation. It is necessary to develop more complex approach. In a puff model, this consists in representing the release of pollutant as a succession of discrete instantaneous releases, each of which is modeled as a Gaussian puff diffusing in the course of time. The center of mass of each puff is advected by a speed field which is supposed uniform but evolves in time. At a given instant, the concentration in any point in space is obtained by adding the contributions of all the puffs produced since the beginning of the release. The principle of this type of model is illustrated on *Figure A8*.

Figure A8: Scheme of a Gaussian puff dispersion model



The black dot represents the location of the source. Circles illustrate the puffs used to discretize the plume.

The choice of the time step used to discretize the release must be adjusted in order to correctly represent:

- the kinetics of the release;
- the evolution of meteorological conditions;
- an overlap of different puffs capable of giving the plume a sufficiently “continuous” aspect.

Numerical schemes used for the advection phase of the puffs must be consistent with the type of available meteorological data (continuous or discretized according to given time step). It is generally not necessary to use excessively complex methods, because of the many assumptions made otherwise.

The puff diffusion phase is based on empirical or theoretical parameterizations as already mentioned. In the pX model, computing the σ_i is based on the transit time t of the puff from the source or on the distance traveled x.

During the advection-diffusion phase of the puffs, it is necessary to account for two phenomena: the presence of the ground which may capture part of the pollutants; and the temperature inversion at the top of the limit layer which prevents the vertical diffusion of pollutants. Methods explained in section 1.1. would be used to this end.

2. The diffusion model

This section explains the method used to calculate the diffusion of the puffs. It is based on the computation of standard deviations using empirical formulations (Doury, Briggs, Pasquill) which are adapted to account for modifications over time in the stability conditions of the atmosphere.

The model uses a Gaussian model of atmospheric dispersion for an instantaneous release from a point source. The distribution of concentration in space is modeled at any given time by an analytic Gaussian formula which features the standard deviations σ_x, σ_y, σ_z in the three directions x, y et z. Therefore, the dispersion process — i.e. the spread of the pollution plume — is accounted for by the time evolution of these standard deviations. The time variations in standard deviations are directly related to the turbulence of the atmospheric flow; this in turn depends upon two effects:

- the state of thermal stratification;
- the shear of wind due to its friction with the ground.

Operational models of atmospheric dispersion generally use theoretical and/or empirical parameterizations which link the evolution of standard deviations to the dynamic and thermal characteristics of the flow. Two types of parameterizations are generally distinguished:

- ***Parameterizations by classes***. The data necessary to precisely qualify the state of thermal stability of the atmosphere is not often available making it necessary to evaluate it from a few basic values (wind speed, presence or absence of clouds, etc.). A simpler and very widespread approach consists in using a limited number of stability classes, the most frequent being the Pasquill classes and, in France, the Doury classes.
- ***Continuous parameterizations***. The similarity theory of Monin-Obukhov allows describing the thermal stability of the atmosphere in a precise fashion through a parameter called the called the Monin-Obukhov length. New parameterizations of the standard deviations have been proposed based on this formalism which today tend to replace the approach by classes (such formulations are currently being developed for pX).

3. Modeling mechanisms involved in deposition

Pollutants transported by the flow can deposit onto the ground in two ways: through reactions between the ground surface and pollutants present in the neighboring of the ground (dry deposit); and/or by scavenging of the entire cloud by rain (humid deposit). These two phenomena lead to, on the one hand, a reduction in air concentrations and, on the other and, to a transfer of pollution to the ground, vegetation or aquatic systems. It is therefore important to take them into account when studying atmospheric dispersion.

3.1 Dry deposits

Dry deposits can take place through several mechanisms (whatever the nature of the ground) such as absorption, dilution into water, particulate deposit. It is generally considered that the deposition flow (the mass of pollutant deposited by unit of surface and unit of time) is proportional to the concentration of pollutant in the air in the neighborhood of the ground Sehmel[69]:

$$\Phi_{\text{dépotsec}}(x,y,t) = V_d\, C(x,y,z=0,t) \qquad (3.1)$$

where V_d is a speed of deposit. This is controlled by different mechanisms:

- ***Aerodynamic resistance.*** This is the limited capacity of turbulent flows to diffuse pollutants from the cloud to the ground. If the flow is not turbulent (for instance in a stable atmosphere), the speed of deposit will be limited by the speed of diffusion of pollutants in the atmosphere.
- ***Resistance of the sublayer.*** The air layer located close to the ground constitutes a limit to the deposition of matter because the transport of species can only be performed by molecular diffusion for gases and by inertia for particles. This limiting mechanism is controlled by the roughness of the surface.
- ***Resistance of the surface itself.*** This is related to the physicochemical affinity between the materials present on the ground surface and the pollutant.
- ***Sedimentation processes.*** In the case of particles, inertial phenomena induce a deposition velocity.

Sehmel[69] provides a list of characteristic values for the total deposition velocity under different conditions (nature of the pollutants, of the surface, of wind, etc.). These values vary between 10^{-3} cm.s^{-1} and 180 cm.s^{-1}. In the pX model, deposition velocities are defined for each isotope. It is supposed that they are constant in time and uniform in space, that is to say independent from the nature of the ground.

The quantity deposited by unit of surface during a time dt for an isotope endowed with deposition velocity V_d is therefore:

$$Q_{\text{dépot sec}} = V_d \,.\, dt \,.\, C(x,y,z=z_{\text{sol}}) \qquad (3.2)$$

In order to model decreasing concentrations in the plume due to deposition, it is necessary to subtract deposited quantities from the mass of pollutants transported by the cloud. In the pX model, this is supposed to be uniformly distributed among puffs ("decrease at the source") and is simply represented by a decrease in the quantity of pollutant contained in the puff:

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[69] Sehmel, G. A., 1984. *Deposition and resuspension*. In Atmospheric Science and Power Production, NTIS report.

$$\frac{dM}{dt} = -\iint_{sol} \Phi_{\text{dépotsec}}(x,y,t)\,dx\,dy = -V_d \iint_{sol} C(x,y,z=0,t)\,dx\,dy \qquad (3.3)$$

Considering that concentration due to a puff can be written in the following form (equation 1.5):

$$\begin{aligned} &C(x,y,z,t) = M(t).\text{gauss}_x(x,t).\text{gauss}_y(y,t).\text{gauss}_z(z,t) \\ &\text{avec} \quad \int_{-\infty}^{+\infty} \text{gauss}_x(x,t)\,dx = \int_{-\infty}^{+\infty} \text{gauss}_y(y,t)\,dy = \int_{z_{sol}}^{+\infty} \text{gauss}_z(z,t)\,dz = 1 \end{aligned} \qquad (3.4)$$

The evolution over time of the mass of pollutant transported by the puffs then writes:

$$\frac{dM}{dt} = -M(t).V_d.\text{gauss}_z(z=0,t) \qquad (3.5)$$

In the pX code, relation 3.5 is discretized with respect to time:

$$M(t+dt) = M(t)\left(1 - V_d.\text{gauss}_z(z=0,t)dt\right) \qquad (3.6)$$

3.2 Humid deposition (scavenging)

When rain falls through polluted air, pollutants (whether in gaseous or particulate form) are partly absorbed by raindrops and thus dragged down to the ground. These dissolved pollutants disappear from atmospheric air and are eventually transferred to groundwater or water courses (as, for instance in the case of acid rains). This atmospheric scavenging phenomenon is called humid deposition. It is important to account for these phenomena because they contribute to reduce pollution in the atmosphere and increase it in other media.

In the pX model, scavenging by rain is considered to lead to a homogeneous reduction in pollutant concentration in each puff. Rain is supposed homogeneous in space over the entire computation domain. Supposing that rain falls vertically, the quantity deposited onto the ground by area and time unit can be modeled by:

$$\Phi_{\text{dépot humide}}(x,y,t) = \alpha P \int_0^{+\infty} C(x,y,z,t)\,dz \qquad (3.7)$$

where P represents the intensity of rain (in mm.h^{-1}) and α a constant relative to each isotope. Using relation 3.4 to describe the concentration field caused by a puff, the deposited quantity during time dt writes:

$$Q_{\text{dépot humide}}(x,y,t) = \alpha.dt.P.M(t).\text{gauss}_x(x,t).\text{gauss}_y(y,t) \qquad (3.8)$$

Generally, the value of α is taken equal to 10^{-4} mm^{-1}.h.s^{-1}. The efficiency of scavenging is therefore uniform for a puff; it only depends on the scavenging constant associated with the species transported the puff. As was the case previously, the value does not change during the computation; the rate of reduction of concentrations due to scavenging in a puff can be written as:

$$\frac{dM}{dt} = -\iint_{sol} \Phi_{\text{dépot humide}}(x,y,t)\,dx\,dy = -\alpha P M(t) \qquad (3.9)$$

In the pX model, the above equation is discretized by:

$$M(t+dt) = M(t)(1 - \alpha P.dt) \qquad (3.10)$$