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IMPROVEMENT OF THE ASSESSMENT OF THE EXTERNAL COSTS OF SEVERE NUCLEAR ACCIDENTS

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ExternE - Task 1.5 Accidents

Improvement of the Assessment of Severe Accidents

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Contents

Introduction

Within the framework of the ExternE project, the cost associated with a nuclear accident was derived on the basis of the economic module available in the COSYMA code (based on the "direct" economic loss associated with health and environmental consequences), including further considerations on the probability of occurrence of the different accidental scenarios as well as specific values for health effects. At that period of time, it was clearly pointed out that this approach was limited and that there was a need for further investigation in order to deal with the risk perception. In this regard, first proposals were presented by Anil Markandya *et al.* in the chapter on the valuation of a nuclear accident in the economic valuation report of the ExternE project.

The scope of the task presented in this document was to point out some recent results which emerge in the evaluation of the consequences of a severe accident and to make some proposals for taking them into account in the accounting framework methodology developed for the evaluation of the external costs of the fuel cycles.

In order to improve the assessment of severe accidents, the following topics have been considered and are divided into two main parts:

Improvement of the consequences calculations:

- analysis of the relevant accidental scenarios for the evaluation of the consequences and their associated probabilities;
- integration of the indirect costs evaluation;

Integration of the risk perception:

- critical review of practical risk aversion approaches in the external cost studies;
- empirical survey: expert versus expert risk perception;
- expected utility approach;
- economics of risk and uncertainty.

This document contains the contribution of the different teams involved in this task. It does not solve all the issues associated with the calculation of the external costs of a severe accident, but tries to set up the methods available for this calculation as well as to point out the questions concerning the integration of risk perception.

PART 1: IMPROVEMENT OF THE CONSEQUENCES CALCULATIONS

1.1 External Costs of the Nuclear Fuel Cycle: Source Terms and Probabilities

Véronique Tort (CEPN)

Within the assessment of the external costs of the nuclear fuel cycle, the evaluation of a severe nuclear accident plays an important role. To date, the methodology generally used to evaluate impacts due to accidental releases is based on expected damages. Risk is defined as the summation of the probability of the occurrence of a scenario leading to an accident multiplied by the consequences resulting from that accident over all possible scenarios. The results are very dependent on the values for the probability of the occurrence of accidental releases, the magnitude of the release, and the exposure scenarios evaluated.

Probabilistic safety assessment (PSA) methodologies have been developed to evaluate the potential causes of an accident, the possible probabilities of occurrence, and the expected environmental releases. The published results of past studies can be used to estimate the necessary input for this assessment. A large number of PSA have been carried out for light water reactors, in particular in the US. The probability of core melt accidents and the subsequent release of radioactive material to the environment depends on the origin of the accident, the performance of safety systems, and the reactor containment. If the containment suffers massive failure or is by-passed, a substantial fraction of the volatile content of the core may be released to the environment, if the containment remains intact the release will by comparison be very small.

A. French National Implementation

A complete assessment of potential severe accidents would require a comprehensive PSA of many possible accident scenarios. This level of effort does not fall within the scope of this project. In addition, specific data on potential source terms and probabilities for potential accidents at French nuclear power plants were not available to the project. As a result, hypothetical scenarios have been analysed to demonstrate the risk-based assessment methodology and provide indicative results. The European accident consequence code COSYMA was used to carry out the analysis of the impacts.

Source Term

In order to provide an idea of the risks and impacts, and the sensitivity of these results, four different source terms were analysed. The worst case release characteristics evaluated in this study were taken, for convenience, to be those assumed for source term ST2 in a OECD-NEA/CEC inter-comparison study, based on those reported in US NUREG-1150. The ST2 source term assumes a massive containment failure at a 1250 MWe reactor, that results in the total release of noble gases from the core, 10% of the more volatile elements, such as caesium and iodine, and smaller percentages of other elements. It is assumed to occur in a single release phase without energy. The characteristics of the fraction of core released by radionuclide group are provided on the Table 1. This source term is considered to be indicative of containment bypass or breach.

The ST21, ST22, and ST23 source term releases are a factor of 10, 100 and 1000 times lower than ST2 and represent a core melt with no containment breach. The lowest release is considered to be indicative of an accidental situation where the safety systems function as designed. One of the intermediate source terms, which corresponds to a release of about 1% of the core, is in the same order of magnitude as the reference accident scenario considered by the French national safety authorities.

Probability of Accident

The probability of an accident resulting in a core melt at a nuclear reactor will have a major influence on the results of this assessment. Data available on actual accidents are not sufficient to provide a statistically significant value. In this evaluation, the probabilistic assessments that have been made of existing and planned reactors are reviewed to provide a basis for the indicative assessment. Based on the PSA that has been carried out for the French 1300 MWe PWR, a probability of a major core melt at a 1300 MWe PWR of 1E-5 per reactor.year was assumed.

The conditional probabilities of core melt for each of the four release scenarios considered, taken from the US Oak Ridge National Laboratory external costs study and based on the NUREG-1150 report, used for the purposes of this indicative assessment are presented in Table 1.

Table 1: Nuclear Accident Source Terms and Probabilities Used in the French National Implementation for a 1300 MWe PWR

Release category	Release fraction of the core inventory						Proba. of occur. per year
	Noble gases	I	Cs	Te	Alk. earth metals and noble metals	Metal oxide	
ST2	1	0.1 *	0.1	0.1	0.01	0.01	2-3 10^{-6}
ST21	0.1	0.01	0.01	0.01	0.001	0.001	
ST22	0.01	0.001	0.001	0.001	0.0001	0.0001	
ST23	0.001	0.0001	0.0001	0.0001	1 10^{-5}	1 10^{-5}	7-8 10^{-6}

* organic I : 0.001

B. Review of Other Nuclear Accident Source Terms and Probabilities

German National Implementation

The German national implementation report (prepared by the University of Stuttgart) takes into account six release scenarios. A probability of occurrence is associated with each scenario, based on values compiled by KfK in 1994. These probabilities vary between 10^{-6} and 10^{-8} per year for a 1300 MWe PWR. The Table 2 shows the release fractions of the core inventory and the associated probabilities. The definitions of the scenarios are:

Scenario 1: Extensive containment failure
Scenario 2: Leakage of the primary circuit in the containment annulus
Scenario 3: Steam generator - tube rupture without sufficient water reservoir in the damaged steam generator
Scenario 4: Steam generator - tube rupture with sufficient water reservoir in the damaged steam generator
Scenario 5: Increased leakage of the containment through the containment annulus and auxiliary building
Scenario 6: Containment venting at 0.6 MPa and release via filter and stack

Table 2: Nuclear Accident Source Terms and Probabilities Used in the German National Implementation for a 1300 MWe PWR

Release category	Release fraction of the core inventory							Proba. of occur. per year
	Noble gases	I	Cs	Te	Alk. earth metals	Noble metals	Metal oxide	
1	1		0.7		0.36	$1\ 10^{-5}$	0.034	10^{-7}
2	1	0.37	0.37	0.23	0.14	$2.5\ 10^{-6}$	0.012	10^{-7}
3	0.17	0.15	0.15	0.05	$6.4\ 10^{-4}$	$8.8\ 10^{-8}$	$2.1\ 10^{-9}$	10^{-8}
4	0.17	0.025	0.025	0.15	$1.2\ 10^{-4}$	$1.7\ 10^{-8}$	$3.8\ 10^{-10}$	10^{-8}
5	1	0.0078	$3.5\ 10^{-4}$	0.0021	$1.4\ 10^{-4}$	$3.6\ 10^{-7}$	$1.1\ 10^{-5}$	10^{-6}
6	0.9	0.002	$3.3\ 10^{-7}$	$3.5\ 10^{-6}$	$1.9\ 10^{-7}$	$6.4\ 10^{-10}$	$3.3\ 10^{-8}$	10^{-6}

The French and German release scenarios are not directly comparable as the most pessimistic French release scenario fractions are slightly lower than the German third scenario, except for noble gases and metals.

UK NRPB Hinckley Point Study

The estimates of the frequency of occurrence of severe reactor accidents (core melt, containment bypass, and design basis accidents) have been reported for the UK Hinckley Point PWR by NRPB. Twelve different source terms for a PWR core melt (degraded core) accident were assessed. The frequency of occurrence for the 12 release scenarios range from about 2 10^{-10} to 6 10^{-7} per year with a total probability of about 10^{-6}. Table 3 presents the probability of occurrence of each scenario and the fractional releases from the reactor inventory.

Switzerland

A report prepared in 1993 for the Swiss Federal Nuclear Safety Inspectorate (HSK) presents a regulatory evaluation of the Mühleberg probabilistic safety assessment. In this study a set of nuclear scenario accidents is analysed, as well as the associated probabilities. But these values are specific to a BWR reactor and are not directly applicable to a PWR reactor which is a different technology. Nevertheless, for information, some orders of magnitudes can be given:

- for the different scenarios considered, the release fractions vary between 0.99 and 0.05 for noble gases, 0.15 and 2 10^{-6} for iodine,
- the probabilities of occurrence vary between 9.3 10^{-6} and 4.4 10^{-10} per year. The total core damage frequency is 1.2 10^{-5} per reactor and per year,
- the total core damage frequency of 1.2 10^{-5} is compared to the NUREG-1150 value for Peach Bottom US nuclear power plant of 9.9 10^{-5} per reactor and per year.

Table 3: Release Fractions and Probabilities for the 12 UK Source Terms

Release category	Frequency of occur. (per year)	Fraction of core inventory released (1)							
		Xe-Kr	organic I	inorg. I-Br (2)	Cs-Rb	Te-Sb	Ba-Sr	Ru (3)	La (4)
1	2.4 10^{-9}	0.9	0.007	0.7	0.5	0.3	0.06	0.02	0.004
2	4 10^{-10}	0.9	0.006	0.7	0.4	0.35	0.05	0.2	0.003
3	2.4 10^{-9}	0.8	0.006	0.6	0.6	0.1	0.08	0.02	0.002
4	5.9 10^{-10}	0.8	0.006	0.2	0.2	0.25	0.02	0.015	0.003
5	8.0 10^{-9}	1	0.007	0.06	0.3	0.5	0.04	0.03	0.006
6	4.2 10^{-9}	0.9	0.006	0.009	0.2	0.04	0.02	0.007	7 10^{-4}
7	1.2 10^{-9}	0.8	0.006	0.008	0.002	4 10^{-4}	3 10^{-4}	8 10^{-5}	8 10^{-6}
8	2.0 10^{-10}	0.8	0.006	0.006	5 10^{-6}	1 10^{-6}	7 10^{-7}	2 10^{-7}	2 10^{-8}
9	5.2 10^{-9}	0.3	0.003	8 10^{-4}	8 10^{-4}	0.001	9 10^{-5}	7 10^{-5}	1 10^{-5}
10	4.2 10^{-9}	0.006	2 10^{-5}	2 10^{-5}	1 10^{-5}	2 10^{-5}	1 10^{-6}	1 10^{-6}	2 10^{-7}
11	6.2 10^{-7}	0.06	3 10^{-5}	3 10^{-5}	3 10^{-5}	3 10^{-5}	3 10^{-6}	2 10^{-6}	4 10^{-7}
12	5.1 10^{-7}	0.05	3 10^{-5}	8 10^{-6}	1 10^{-6}	2 10^{-7}	1 10^{-7}	4 10^{-8}	4 10^{-9}

(1) The specified fractions of the core are assumed to be released uniformly over the specified release duration apart from UK1. The release fractions apply to stable isotopes of the specified elements.
(2) The iodine and bromine are assumed to be released in an elemental form.
(3) Includes Ru, Rh, Co, Mo and Tc.
(4) Includes Y, La, Zr, Nb, Ce, Pr, Nd, Np, Pu, Am and Cm.

Chernobyl Source Term

The different source terms presented in this paper can be compared to the order of magnitude of the releases of Chernobyl shown in Table 4.

Table 4. Current estimate of radionuclide releases during the Chernobyl accident (modif. from De95)

Core inventory on 26 April 1986			Total release during the accident	
Nuclide	Half-life	Activity (PBq)	Percent of inventory	Activity (PBq)
^{33}Xe	5.3 d	6 50	100	6500
^{131}I	8.0 d	3 20	50 - 60	~1760
^{134}Cs	2.0 y	180	20 - 40	~54
^{137}Cs	30.0 y	280	20 - 40	~85
^{132}Te	78.0 h	2 70	25 - 60	~1150
^{89}Sr	52.0 d	2 30	4 - 6	~115
^{90}Sr	28.0 y	200	4 - 6	~10
^{140}Ba	12.8 d	4 80	4 - 6	~240
^{95}Zr	1.4 h	5 60	3.5	196
^{99}Mo	67.0 h	4 80	>3.5	>168
^{103}Ru	39.6 d	4 80	>3.5	>168
^{106}Ru	1.0 y	2 10	>3.5	>73
^{141}Ce	33.0 d	5 60	3.5	196
^{144}Ce	285.0 d	3 30	3.5	~116
^{239}Np	2.4 d	27 00	3.5	945
^{238}Pu	86.0 y	1	3.5	0.035
^{239}Pu	24 400.0 y	0.85	3.5	0.03
^{240}Pu	6 580.0 y	1.2	3.5	0.042
^{241}Pu	13.2 y	170	3.5	~6
^{242}Cm	163.0 d	26	3.5	~0.9

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1.2 Integration of the Indirect Costs Evaluation

Thierry Schneider (CEPN)

A. Introduction

Further to the classical evaluation performed for the health and environmental consequences of a nuclear accident, the decrease or interruption in most economic activity (essentially agricultural and industrial production) in the affected territories for a significant period of time should also be considered. The importance of this interruption notably depends on the size of the accident. In terms of monetary indicators, this disturbance of economic activity will mainly induce a loss of value added (this indicator corresponds to the different direct and indirect incomes of the various "economic agents").

An economic evaluation of such indirect effects can be based, with some limitations, on the use of Input-Output methods, which represent the interchanges between the different economic sectors of a region or a country. Such methods have been developed, in the framework of the National Accounting system, to describe the structure of the economy and to study the evolution of the economy according different scenarios.

In the case of the cost assessment of a nuclear accident, these methods are useful in analysing amplified impacts on the regional and national economic system as far as the areas affected by the accident have some interrelationships in terms of demand and supply of goods and services. In fact, the decrease or interruption in the economic activity of the affected areas induces a loss of demand and supply in the regional and national economies as well as some economic disturbances in the regions where the evacuated or relocated populations are living following the accident. Introducing these modifications into the relationships described by the input-output matrix allows one to derive the indirect economic consequences associated with the occurrence of a nuclear accident. Such indirect effects simply reflect the cost related to the adaptation of economic activities following a nuclear accident above the direct costs of this accident (Proult and Desaigues, 1993).

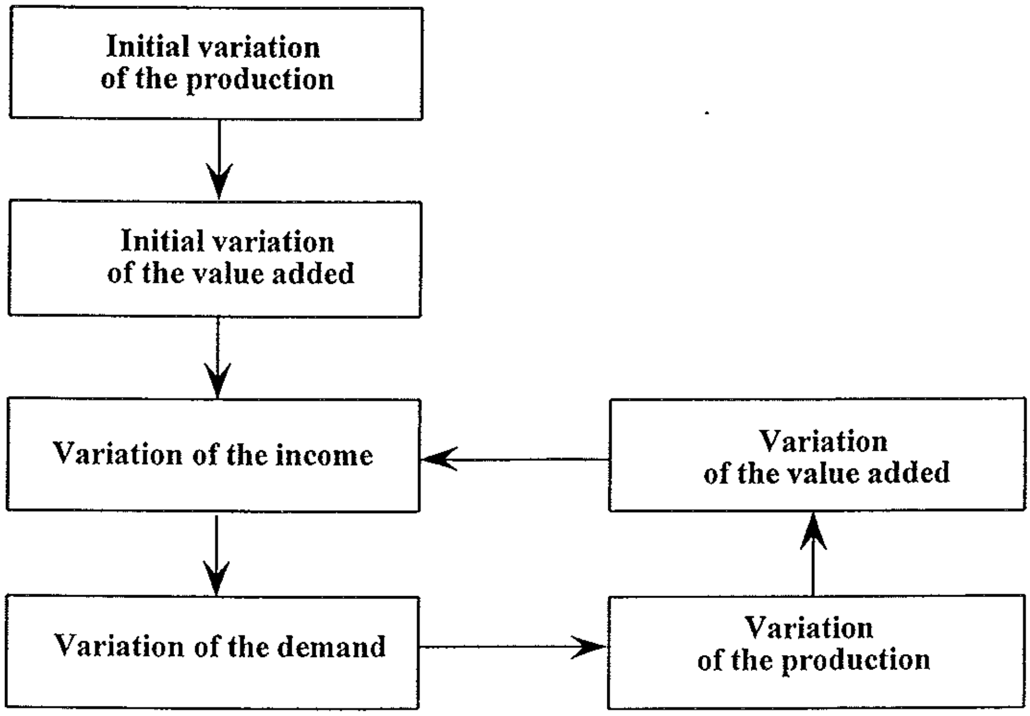
B. The Mechanisms of Modification of the Economy

The calculation of the direct effects associated with a nuclear accident takes into account the loss of the various productions directly affected by the accident, while the input-output method is useful for estimating the indirect consequences of these initial losses of production. It essentially refers to the global economic losses.

The decrease or the interruption in production in the affected areas will lead to a reduction of the demand for goods and services of the populations living and/or working in these areas because of the loss of incomes. Such a reduction of the demand will progressively affect the different fields of the economy, and not only consumption products. Notably, intermediate consumption goods will also be affected inducing new reductions in production in the affected region which will affect the whole economy.

We are faced with a cyclical mechanism: a change in demand leads to a change in resource production, and this additional decrease in production of resources corresponds with a new decrease in value added, and hence in wages. This in turn leads to a new decrease in demand, lower than the initial shock, and so forth until a stationary state is reached, when induced decreases at each step approach zero. The main initiator of this mechanism is the final consumption of the population which induces the iterative adjustment of supply. This mechanism is described on Figure 1.

Figure 1: Framework for the Calculation of the Consequences on Economic Activities



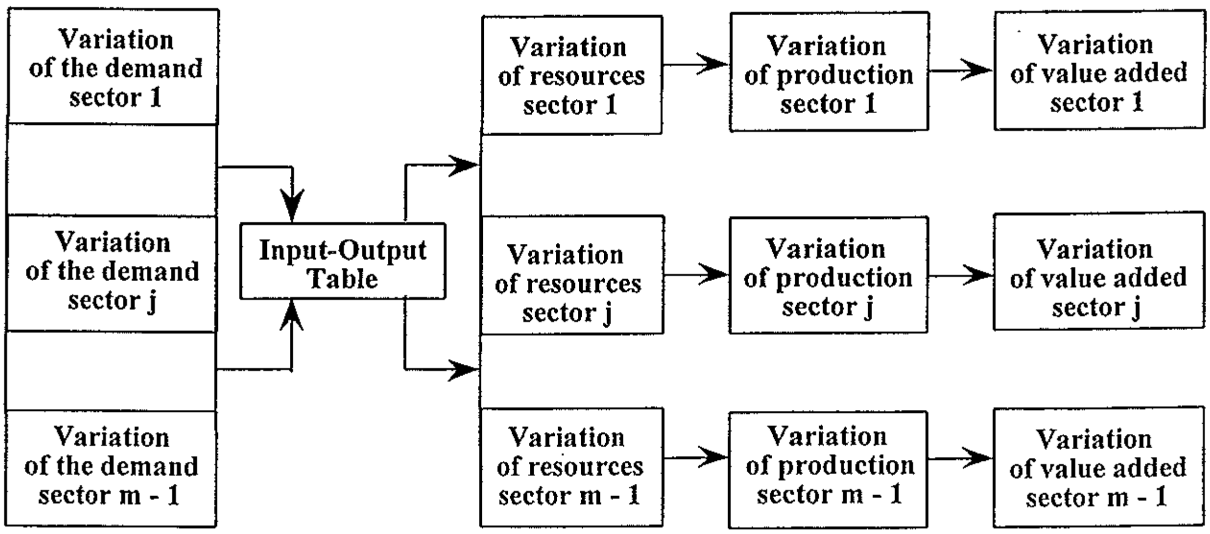
It should be noted that this mechanism is representative of a situation where the affected areas are significant in size compared to the region in which economic activity is being considered. Otherwise, in the event of a small-scale accident, the loss of production capacities will be easily compensated by increasing the regional economic activity.

Alternatively, it is possible that an economic sector is largely affected by the accident (for example, most agricultural production). In this case, the supply difficulties which would occur in this sector would induce an adjustment through an increase of prices and/or an increase of import. Thus, modifications in the balance of trade would also have to be considered.

C. Description of the Calculations

Because of the disturbances in different economic sectors, it is necessary to use a model of the economy: the input-output tables. According to the initial variation of demand in the different sectors of the economy, the calculation of the indirect consequences on the regional and national economy can be derived from these tables. The general model for the different sectors of the economy (number of sectors: m) is described in Figure 2. The first step is characterised by a variation of the demand which is distributed between the different sectors (except the trade sector which has no production). On this basis, using the technical coefficients (input-output tables) characterising the relationships between the different sectors at the regional or national levels, the second step allows us to derive the variation of resources in the various sectors, leading to a variation of production and finally to a variation of the value added. Such a mechanism can be repeated till a new economic equilibrium between the various regional and national sectors of the economy is reached (Cour, 1994).

Figure 2. The Use of the Input-Output Tables: From the Variation of Demand to the Variation of Value Added



D. Implementation of the Indirect Cost Calculations

In practice, the difficulties for the application of these methods are associated with:

- the compilation of suitable Input-Output tables,

- the effort required for calculation (particularly, since data is available either at the regional level or the national level, it is generally necessary to determine the value of the parameters associated with a more restricted area corresponding to the territories seriously affected by the radioactive releases),
- the definition of non-directly affected areas as far as the economic aspects are concerned (some effects may extend over the entire country).

Although detailed calculations can be performed for each accidental scenario and each specific area, a set of assumptions has been adopted and applied to a specific accidental scenario in order to give an example of the order of magnitude for the indirect costs, and to suggest, on this basis a multiplying coefficient to be applied for the sake of simplification in the evaluation of the total cost of the nuclear accident.

For this purpose, a nuclear accident leading to a release of about 10% of the core (corresponding to the highest source term considered in the NEA and EC exercise (OECD, 1994)) has been considered to occur in the nuclear power plant of Nogent-sur-Seine. In order to simplify the calculation of the indirect costs, the affected region is assumed to be the administrative region of "Champagne-Ardennes" [2]. Although the dispersion model leads to a slightly different geographical area affected by the releases, most of this administrative region is concerned with the releases and the total surface of the affected area is not significantly different to the total surface of the administrative region. Using the COSYMA code (Ehrhardt and Jones, 1991) and the value of life adopted in the ExternE project (Dreicer, Tort, and Margerie, 1995) the following results were derived:

- in terms of the regional gross domestic product, this accident is supposed to induce an indirect cost of about 10 % during the first two years;
- similarly, it represents about 0.2 % of the national gross domestic product;
- the indirect costs lead to an increase of 25 % of the local direct external costs of a nuclear accident.

In fact, based on this calculation, one can considered a multiplying coefficient of 1.25 to be applied to the local direct external costs calculations in order to derive the total external costs of the accident. This simplification seems to be reasonable when one considers accident scenarios leading to significant radioactive releases into the environment.

E. Additional Comments on the Method

Through the use of this method, probably the most interesting conclusion is that the positive effects in the areas not directly impacted by the countermeasures could overcome some negative effects in the affected regions. However, it is also recognised that for some scenarios this can be only partially true, given the limited capacity to model ex-ante some effects like these mentioned on tourism or on food marketing.

In fact, some effects may occur on the level of prices, for example, in the region where the people have been evacuated or relocated, the price of renting a home may generally increase if demand is significant. On the other hand, the increase of activity associated with the implementation of the countermeasures or the investments in reconstruction of buildings and infrastructure, may have positive effects on the national economy. Nevertheless, for the calculation of these consequences, one has to consider the increasing amount of resources required, and thus to take account of the opportunity cost.

Although this method is rather well designed from a modelling point of view, it is necessary to be cautious in order to avoid double counting of the same effect. It is also important to identify the relevant effects according to the size of the accident, its duration, the size of the evacuated areas, the economic situation of the affected areas, and the regional and national contexts, keeping in mind the assumptions adopted for the calculation procedures. This is particularly true for the application of the method in contexts other than the one presented above (different types of severe accidents lead to different effects and different durations of perturbation on daily life).

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PART 2: INTEGRATION OF THE RISK PERCEPTION FOR THE CALCULATION OF THE EXTERNAL COSTS ASSOCIATED WITH SEVERE ACCIDENTS

2.1 Critical Review of Practical Risk Aversion Approaches in External Cost Studies

Alexander Gressman (IER)

A. Overview of Results: The Calculation of Nuclear Accidents in Published Studies on External Costs.

External cost studies published since 1989 have shown considerable differences in the results of the evaluation of external costs of nuclear reactor accidents. Table 2.1.1 shows the contribution of reactor accidents to external costs that have been calculated in different studies (damages by normal operation of the nuclear fuel cycle are not included in these numbers.) With one exception - the US study of Oak Ridge National Laboratory and Resources for the Future - the fatal health effects are by far the highest contributors to the total estimates, in comparison to all other effects, including evacuation measures, agricultural losses and other damages to property.

From Table 2.1.1 it can be seen that the expected value of damages by hypothetical severe accidents has a wide variation. A critical and detailed comparison of all these studies regarding the approach and methodology of their calculation reveals that differences in results have two separate causes (Friedrich *et al.*, 1996). The first is the approach to gathering the expected values of hypothetical accidents. The second is the different ways in which these studies have attempted to solve the question of whether risks with very low probability but causing extremely high levels of damage should be valued using only the expected value. As this second question is of primary interest in the present project task, these approaches to integrate "risk aversion" into the calculation of values will be examined and critically reviewed in the next section (B)

The first question, that of the "sources" of expected values, can be dealt with briefly. The main reason for differences is that some earlier studies are guided by the assumed damages of the Chernobyl reactor accident and connect these source terms with the probability of a non-controlled event for West European or American nuclear reactors. Hohmeyer (1989) was the first one to use this approach, and the studies of Ottinger (1990) and Ewers/Rennings (1992) were influenced by the Hohmeyer study - see e.g. Friedrich (1995).

Recent studies use the results of probabilistic risk studies both for release scenarios and for probabilities. There is a common consensus that this should be regarded as the state of knowledge. A comparison of these results (see Table 2.1.1) - leaving aside the analysis of risk-aversion and the calculations influenced by Hohmeyer, as explained above - shows that some of them are in a comparable range, and the remaining larger differences can be plausibly accounted for. These values are in an interval between 0.0008 and 1.02 mECU/kWh. Excluding the value of 1.02 mECU/kWh given by Infras/Prognos study (explained in section B), this range decreases to 0.0008 - 0.35 mECU/kWh.

Table 2.1.1 Overview of Results: Damage Costs of the Impacts of Reactor Accidents (separated from the overall results of the studies where necessary) - in mECU/kWh

Study	Fluctuation margin of damage costs for nuclear accidents	Particulars of results
Hohmeyer (1989)	6.0 - 60	study takes impacts of the Chernobyl accident as a basis
Hohmeyer (Supplement, 1990)	17.4 - 105	Chernobyl accident taken as a basis (see above)
Friedrich *et al.* (1990)	0.04 - 0.35	
Ottinger *et al.* (1990)	18.4	Chernobyl accident taken as a basis (see Hohmeyer)
Pearce *et al.* (1992)	0.00085 - 0.0021	expected value (without risk aversion)
(The revised study of Pearce (1995) does not lead to a change in results for nuclear accidents)	0.25 - 0.625 / 3.38	with two alternative approaches of risk aversion
Infras/Prognos (1994)	0.006 - 1.02	expected value (without risk aversion)
	11.4 - 189.6	risk aversion included by using the standard deviation of damage instead of the mean
ORNL/RFF (1995)	SE: 0.083 SW: 0.0477	SE: South-east site (East Tennessee) SW: South-west site (New Mexico) non-health effects (property etc.) are higher by far than damages of health; health effects calculated with 3 % discount rate; non-health effects include "onsite" (plant-related expense) such as loss of utility assets and utility site cleanup
ExternE (CEPN) (1995)	0.0014 - 0.0235	costs of reactor accidents only calculated with 0 % discount rate
Krewitt (1996)	0.0085 / 0.002	0 % discount rate / 3 % discount rate
Rowe *et al.* (1995)	0 - 0.08	share of the cost category "accidents" is not separately identifiable from available data source
Ewers/Rennings (1992)	21.5	Chernobyl accident taken as a basis (see Hohmeyer)
Hirschberg/Cazzoli (1994)	0.0008 - 0.031	
Wheeler/Hewison (1994)	0.0014 - 0.0016	

Fractions of these results that may be covered by insurance and thus internalized are included.

Source: Friedrich *et al.* (1996); Greßmann, Friedrich (1996).

A number of points concerning the above table should be noted. First it should be mentioned that the problem of insurance costs was not discussed, or at least did not enter into the calculations in the external cost studies listed in Table 2.1.1 (including the ExternE study). Thus, the figures in Table 2.1.1 are labeled as "damage costs" and not "external costs". This refers to the fact that part of these damage costs are probably born by the electricity generating company because of liability regulations through international conventions and national funds. For example, in Germany nuclear power plant operators are fully liable for all damages connected with disruptions of operation or accidents, even if not due to negligence. Insurance contracts are essential and have to be taken out with a total policy value of DM 500mn. for each reactor, according to the German nuclear judicial cover precaution directive (Atomrechtliche Deckungsvorsorge-Verordnung) (Friedrich, 1993; Masuhr *et al.*, 1992). In addition, the federal government is liable for a further DM 500mn. under the terms of a release obligation.

In the United States, the "Price-Anderson Act" will internalize damages of $200 million, and in special cases up to $7 billion (Lee, 1995). Therefore, the ORNL/RFF study assumes that all occupational damages, on-site damages, and immediate health effects may be internalized. Insurance duties as existing in Germany or the United States cannot fully compensate for all of the costs should a severe reactor accident occur. This is obvious since the most important component of nuclear reactor damages, the statistical deaths evaluated by using the "value of a statistical life", cannot be interpreted as "compensation payments for actual deaths", not even for the heirs. This is pinpointed in all studies that handle the value of a statistical life; see e.g. (Friedrich, 1993).

The published external cost studies, therefore, only consider the problem of insurance costs in a qualitative way and offer rather vague speculation about the percentage of certain damage categories which might be regarded as internalized (Rennings, 1995). Thus, there seems to be a need to go into more detail to cope with the question of internalization. "Usual" occupational accidents are referred to in a similar way for all fuel cycles, but obviously these are of greater importance for nuclear accidents.

Damages that are definitely not external costs are typically onsite expenses - the losses attributable to the accident that affect the power-generating company itself (e.g. the costs of replacing the nuclear reactor and other destroyed productive resources). That means, however, that the "sum of damages" in Table 2.1.1 signifies a limited calculation of total damage costs because it does not cover the complete (social) amount of damages arising.

The second point about the results of Table 2.1.1 concerns the contribution of health and non-health damages to the results. In addition to health damages (fatal and non-fatal), not all of the studies listed cover further damage components of a reactor accident such as property, agricultural and productivity losses caused by the contamination of residential areas. In the joint CEC/US study (ExternE and ORNL/RFF) these non-health damages seem to be adequately represented in evaluation. But the study by ORNL/RFF (Lee, 1995; ORNL, RFF, 1995) is the only one where these damages to property are much higher than the damages to human health - by a factor of 3, and 22 respectively, depending on the site.

The result of the ORNL/RFF study (ORNL, RFF, 1995) should be discussed in more detail. The characteristics of the American sites and methodology used is quite distinct from the other studies. ORNL/RFF used the accident consequence assessment model MACCS (Modular Accident Consequence Code System), developed by Sandia National Laboratories - that was also used in the study for Switzerland by Hirschberg and Cazzoli (1994). Two accident scenarios were considered: a "massive containment failure" (significant breach of the containment, followed by a major release of fission products) and a "limited containment failure". Given that a severe accident occurs, the conditional probability of the massive containment failure case is assumed as 0.26, the probability of the limited containment failure case as 0.74.

The power plants are (hypothetically) situated in areas nearly empty of population, especially the South-west site in New Mexico - and accordingly this site shows the most extreme ratio of health and property effects. Sites with a comparably low population density cannot be found in a Western European country. To illustrate the difference in population density, the area and population examined in both sites of the ORNL/RFF (1995) study are compared to the respective data of the German site in the study by Krewitt (1996) (Table 2.1.2).

Table 2.1.2 Regional Area and Population in the ORNL/RFF and Krewitt Study

Study	Site	Radius of regional area	Circular area examined (water area included)	Population exposed within the circular area	Average population per square km
ORNL/RFF (1995)	Southeast (Oak Ridge, East Tennessee)	1609 km	8.13 mn. km^2	192.9 mn.	23.7
	Southwest (New Mexico)	1609 km	8.13 mn. km^2	88.6 mn.	10.9
Krewitt (1996)	Southwest of Germany	1000 km	3.14 mn. km^2	335.2 mn.	106.7

Source: ORNL, RFF (1995); Krewitt (1996); own calculations.

Although the ORNL/RFF study examined the effects over a larger distance than the European study by Krewitt, the number of people exposed within this area is much smaller, especially within the area around the Southwest site. The risk per person is much higher in the evacuation area (0 - 16.1 km distance from the plant) and in the local area (16.1 - 80.5 km distance). In addition, the contributions of the evacuation and local area together (both for fatal and non-fatal cancer cases) are only 6 - 7 % (Southeast site) and 9 - 10 % (Southwest site); the sum of health damages is dominated by the damages in the regional area (80.5 - 1,609 km). Therefore, because of the wide-ranging distribution of cancer cases the damage is not primarily influenced by the population density of the immediate surroundings, but rather by the generally lower population density of the USA, compared to Europe. Thus, the estimated number of fatal and non-fatal cancer cases, conditional on the most severe reactor accident considered occurring, is much lower in the ORNL/RFF study than in European studies: only 15,200 (for the massive containment failure case at the Southeast site), compared for example, to about 50,000 in the ExternE study for France (Lee, 1996). On the other hand, ORNL/RFF (1995) calculated all delayed effects with a discount rate of 3 % (with an assumed latency of 13 years for leukemia and 20 years for all other cancers), whereas for example, the ExternE study by CEPN calculated all accidents with a discount rate of 0 %.

The high share of property damages (compared to health damages) is primarily due to the onsite damages categories, the losses associated with the reactor site itself. There are four loss categories "loss of utility assets", "utility site cleanup", "plant decommissioning" and "replacement power". These represents losses to the PWR plant owner. Although the study argues that they will be transferred over the years to the ratepayers, stockholders and taxpayers within and outside the region, these losses are what we typically regard as "internal" costs, and are thus not included in the results of other studies. These four categories together amount to 55 % of all non-health costs for the Southeast site and 80 % for the Southwest site. Their extent is assumed to be independent of the site, with the exception of the power replacement costs which are even higher for the Southwest site.

The remaining contributions to non-health costs consist mainly of the costs for disposal of low-specific activity materials (soil and crops) resulting from decontamination activities, and of interdiction and condemnation costs. For the scenario of a massive containment failure, farmland was interdicted to a distance of 244 km and condemned to a distance of 136 km. Non-farm property was interdicted to a distance of 183 km and condemned to a distance of 41 km (Southeast site). The Southwest site shows only slight deviations from these distances, and since farmland was assumed to be worth considerably less at the Southwest site, much higher costs for the interdiction and condemnation of farmland were incurred for the Southeast site. In total, however, the property damages are only to a minor extent dependent on the population density because of the prevailing effect of the onsite costs. These lead to the extremely high share of non-health costs for the Southwest site.

B. Risk-Aversion Approaches in Practical Studies.

The overall result of the "newer" studies listed in Table 2.1.1 (i.e. the studies that are not influenced by the procedure of Hohmeyer) is that the risks, expressed by their expected value, are rather small, compared to other external cost categories. Obviously, there is a discrepancy between this result and the concern of large parts of the population about nuclear accidents. From an economic point of view, there is agreement that external costs ought to mirror the population's preferences. Therefore, this discrepancy induced some economists to come to a convergence between external costs of risks and the feelings of parts of the population - by taking account of "risk aversion" instead of using only the expectation values of damages. Approaches of this kind are suggested by Pearce *et al.* (1992) and the Swiss Infras/Prognos study (Masuhr, Oczipka, 1994) in their external cost studies, and are used to calculate cost estimates. Both approaches are described and critically reviewed in the following.

As has been noted elsewhere in this report, however, all these approaches treat risk aversion in an *ad hoc* manner. A treatment of risk aversion which has a stronger theoretical foundation based on expected utility and individual preferences is that of Krupnick, Markandya and Nickell (1993).

It should be noted that an opposing position compared to all such risk aversion approaches is taken by some members of the Enquête Commission in a remark about calculations of this kind (referring especially to the Infras/Prognos approach): "The research is bound to serve to quantify external costs (i.e. of electricity generation). In such an investigation, the question of how the individual and society is minded towards risks (venturesome or risk-averse) is out of place." (Enquête Commission, 1995; translated by the author). This shows a rather extreme point of view that seems to neglect the generally accepted focus on individual preferences.

The Ferguson study

The first study where an attempt can be found to quantify, on the one hand, the influence of involuntarity on the willingness-to-pay to stave off risks, and - on the other hand - to estimate a "psychological risk" by a quadratic function, is a work by Ferguson (1991). However, this study is not publicly available, and the following information is only gathered by secondary references in Ewers/Rennings (1992) and Masuhr/Oczipka (1994).

In the valuation, Ferguson uses an estimated readiness to take risks with the following characteristics:

- involuntary risks are weighted double the size of voluntary ones;
- the willingness-to-pay for a defence against risks increases in a quadratic way with extent of damage;
- the willingness-to-pay for a defence against risks increases exponentially when the global ecological equilibrium is threatened (Ewers, Rennings, 1992; Masuhr, Oczipka, 1994). This exponential risk increase function, however, can be said to have no theoretical or empirical basis.

It was envisaged that these assumptions would be tested empirically by a contingent valuation study. However, there is no information available to us about whether such efforts have since been undertaken. This is important to emphasize as some later studies and practical applications refer to the methods used in this study - especially the "risk assessment approach" applied for public projects in the Netherlands (that is described in the following section) which simply seems to copy the approach of using a quadratic function.

An application of the "quadratic approach": Risk assessment in the Netherlands

One example where, in spite of an obviously missing empirical foundation, a quadratic relationship between damage extent and damage probability can be found in a "social indifference curve" is a risk assessment approach applied for public projects in the Netherlands. In this study, explicit goals to shelter human life were established. The concepts of "individual risk" and "group risk" have been introduced for human beings and "collective risk" for ecosystems. What is important here is the group risk defined as "the likelihood per year that a group of at least a certain size will all be the victim of a single accident at one and the same time" (Dutch Directorate General for Environmental Protection, 1989).

This definition is specified more closely by the following explanations: "The group risk should indicate the probability that a certain group of people outside a plant will die due to an accident inside the plant. As such, this risk takes account of the surrounding area. In estimating group risk and individual risk acute deleterious effects are determined on the basis of death up to two or three weeks after exposure," (Dutch Directorate General for Environmental Protection, 1989). From this description it becomes obvious that the risks of severe nuclear accidents are only partly covered by this risk assessment process, since it only comprises the immediate effects or "early deaths" caused by an accident but not the stochastically increased mortality that is spread over a range of a hundred or more years after the accident.

Risks are distinguished into three classes: "negligible risks" (1), "as low as reasonably achievable (ALARA)" risks (2) (i.e. for hazards belonging to this category risk reduction is required where possible) and "non-acceptable" risks (3). It has to be pointed out how the limits, i.e. the margins between the risk categories (1) and (2) and between (2) and (3), are defined. These hazard limits are substantiated by aiming to prevent social disruption caused by the death of a group of people all at once; they can be interpreted as revealing a social marginal rate of substitution between the probability of damage and the number of deaths in the case of damage occurring.

These limits "are applied in new situations in respect of existing and future residential buildings and other similarly vulnerable sites. The limits chosen for the group risk specify that the likelihood of an accident with 10 deaths occurring shall not exceed one in every hundred thousand years and as such aim to prevent social disruption. *Disasters with even more serious consequences lead to correspondingly greater degrees of disruption. It is therefore assumed that an n-times larger impact than 10 deaths should correspond with an n-squared times smaller probability of such an accident occurring ...*" (Directorate General, 1989). The group risk is thus expressed "using the n^2 method, according to which a larger number of victims counts more than proportionally in reducing the likelihood of an incident occurring" (ibid.).

Thus, the margins between the three classes of group risk per activity (death at the same time, n or more people) are defined in the following way:

The maximum permissible risk levels for disasters are defined as 10^{-5}/year for n = 10 or more deaths and 10^{-7}/year for n = 100 or more deaths etc. The corresponding negligible levels are defined as 10^{-7}/year for n = 10 or more deaths and 10^{-9}/year for n = 100 or more deaths etc. (Directorate General, 1989).

It should be added that for the individual risks for combined activities in new situations regarding external safety, the maximum permissible level is defined as 10^{-5}/year and the negligible level is defined as 10^{-7}/year.

An increase in the number of deaths by a factor n in a given situation is thus only acceptable if the probability of this event occurring is a factor n-squared lower for both types of level. As Beroggi *et al.* (1993) arguethis squared term seems to be chosen in a quite arbitrary way, and it was never examined systematically how well this formula actually describes public risk aversion. Thus, this arbitrary approach seems to contradict the high effort that is applied in these evaluations for establishing the underlying framework for risk analysis.

The Pearce studies for Great Britain (1992 and 1995) and the underlying risk aversion study by Rocard and Smets (1992).2.3 The Pearce studies for Great Britain (1992 and 1995) and the underlying risk aversion study by Rocard and Smets (1992)

In the 1992 study commissioned by the UK Department of Trade and Industry, Pearce, Bann and Georgiou from the Centre for Social and Economic Research on the Global Environment (CSERGE) calculate externality adders for a series of fuel cycles situated in Great Britain. For the evaluation of nuclear power hazards, after examining existing studies to date, Pearce *et al.* conclude that (among others) the results of the Ottinger study should not be used for building new reactors. It was decided to take as a basis the number of expected fatal cancers calculated by the National Radiological Protection Board (NRPB), that are quoted in the Ferguson study (1991) mentioned above. These calculations, showing different combinations of possible frequencies (f) and pertinent ranges of death numbers per reactor-year (N), are shown in Table 2.1.3.

Table 2.1.3 Expected Fatal Cancers per Reactor Year, Estimated Probabilities and the Effect of Three Different "Disaster Aversion" Concepts in Accidental Costs

Frequency (f)	10^{-8}	10^{-9}	10^{-10}	10^{-11}
Number of deaths per reactor-year (N)	11,000 - 35,000	46,000 - 150,000	110,000 - 250,000	180,000 - 580,000
Risk aversion I*) (Ferguson) ($f N^2$)	1 - 12	7 - 22	4 - 12	1 - 3
Risk aversion II*) (Rocard/Smets) (300f N)	0.03 - 0.11	0.01 - 0.05	0.003 - 0.01	0.005 - 0.002
Risk aversion III*) ($f N^{3/2}$)	0.01 - 0.07	0.01 - 0.06	0.004 - 0.02	negligible - 0.004

*) The corresponding units of the risk aversion figures, the "disaster aversion adders" used by Pearce *et al.* (1992), are artificial units that are different in all three alternatives.

Source: Pearce *et al.* (1992); (identical figures: Pearce (1995)).

Attendant upon these numbers, Pearce introduces various "disaster aversion" functions that "might be used to reflect the fact that society tends to weight group losses more heavily than single deaths". One of these ("risk aversion I" in Table 2.1.3) - the "square rule", i.e. simply squaring the number of deaths, is adopted by the Ferguson (1991) study - although Pearce concedes that Ferguson "... notes that it is not based on empirical studies. Ferguson states that the relevant UK risk perception studies do not exist to enable selection of empirically based functional forms for 'disaster aversion'". So, in fact, risk is weighted by the number of affected persons as:

$$R' = f \cdot N^2.$$

The next alternative used ("risk aversion II" in Table 2.1.3) is a "disaster aversion" function suggested by Rocard and Smets (1992). Here, the risk of accidents is multiplied by a factor of 300:

$$R' = f \cdot N \cdot 300$$

with f = frequency of an accidental event (per reactor-year)
N = number of affected persons
R' = "rectified" risk by respecting risk aversion

Pearce notes: "... Rocard-Smets claim that their function is derived from work by Bohneblust in Switzerland and Germany and Hubert in France. But they also caution that the factor of 300 could be a factor of 1000 ...". This approach leads to adders of 0.02 - 0.05 pence/kWh (about 0.25 - 0.6 mECU/kWh) - however, it is not comprehensible from the Pearce study how these adders were calculated from the data in Table 2.1.3; nor is the result of 0.27 pence/kWh calculation (3,4 mECU/kWh) that is based on Ferguson.

The succinct remarks of Pearce *et al.* (1992) should be quoted: "Whereas R-S has some empirical foundation, Ferguson's proposal square rule has none. On the other hand, R-S is linear in n and this seems to offend the general institution in the risk aversion literature. Looking at non-linear functions, we illustrate a further possible function of n to the power 3/2 [see the line "risk aversion III" in Table 2.1.3]. This produces similar small adders to the R-S rule."

Self-evidently, a simple linear transformation contradicts the principal idea that people get disproportionately more reluctant the higher the potential damage. There could be at least an idea of justification if these (somehow empirically gathered) factors of 300 (or even 1000) can be understood as a linear approximation of a non-linear function.

A careful examination of the original article by Rocard and Smets (1992) shows that the Pearce study obviously did not completely comprehend what R-S really meant with their factor of 300. So some of the contents of this article should be explained.

Rocard and Smets (1992) define: "The disaster aversion factor is the factor by which the social cost of many deaths that occurs individually (1000 x FF 5 million) needs to be multiplied to calculate the social or political costs of many deaths occurring simultaneously. It reflects the fact that 1000 deaths occurring simultaneously in a disaster in the chemical industry have a much greater impact on French society than 1000 deaths occurring individually in road accidents." This looks in agreement with what we understand as disaster aversion. However, after this quoted definition, Rocard and Smets explain: "The cost of a major accident to society includes many *indirect costs* which would have been avoided or would have occurred much later if the accident had not taken place. ... The aversion factor is a sort of rough measure of the *presumed size of the indirect effects* of an accident *compared with its direct effects*. It expresses the proportionally greater importance attached by decision-makers to major accidents as compared with "ordinary" accidents. Surveys carried out among decision-makers show that *the aversion factor increases*, amongst others, *with the seriousness of the accident*."

The most important features of the study of Rocard/Smets to be highlighted are:

1) The disaster aversion factors are gathered by the comparison of decisions made by *political decision-makers*, not individuals: A footnote where an underlying French study by Hubert is explained states: "French decision-makers' propensity to pay to save a life in a road disaster involving the transport of hazardous substances is about 50 to 100 times higher than their propensity to save a life in an ordinary road accident."

2) The gathered disaster aversion factor of 300 refers to accidents involving about 1000 deaths and should be associated only with accidents of this size. It is said several times in the study that this factor depends on (and increases with) the number of deaths. Rocard and Smets (1992) suggest that "the findings are consistent with the hypothesis that the aversion factor for an accident involving N deaths varies proportionately to the power 2/3 of N (and not to N as can be derived by the Dutch policy)". The pointer to the Dutch policy refers to the official practice of risk assessment in the Netherlands, the question of socially acceptable industrial hazards; this is described above.

3) The disaster aversion factor is supposed to include the addition of property effects, indirect effects and further effects induced by the accidents. Though it is not clear if Rocard-Smets use the same terminology for "direct" or "indirect" effects as this study (for "indirect costs" as we have defined them, see Chapter 1.2), from their description it

can be seen that both the "direct" non-health effects (e.g. lost food, loss of property, relocation etc.), and the "indirect costs" in our sense are included, and all these additional costs of a major accident to society (besides the costs of deaths avoided and compensation for completely and partially disabled victims) are explained as one of the main reasons why governmental officials have an increased (and "over-proportional") interest to avoid large disasters compared to smaller accidents.

4) In the Rocard-Smets study only *non-nuclear* on-site and off-site accidents are mentioned, e.g. in the chemical industry and on the road. If there exists a particular fear and aversion against *nuclear* accidents (beyond the general aversion against large accidents with a comparable number of deaths), and/or an aversion of *individuals* that is not (fully) represented by political decision-makers (see point (1) above), this dimension might be neglected in the empirically found risk aversion factors.

From these points (especially Point 2) it can also be highlighted that the application of the factor 300 by Pearce for all the accident scenarios (see Table 2.1.3) does not seem adequate, especially for accident scenarios with an estimated number of deaths of much more than 1000. If the finding of Rocard/Smets that the "disaster factor" is proportional to $N^{2/3}$ and it will take the value of 300 for N = 1000 is taken as valid, then this would lead to using the formula:

$$\mathbf{R' = f \cdot N \cdot (3 \cdot N^{2/3}) = 3 \cdot f \cdot N^{5/3}} \quad \text{instead of} \quad \mathbf{R' = f \cdot N \cdot 300}$$

(with	f	=	frequency of an accidental event (per reactor-year),
	N	=	number of affected persons
and	R'	=	"rectified" risk by respecting risk aversion).

This would come closer to the other variants of disaster aversion calculations shown in Table 2.1.3.

Two more points should be made about the approach and results of the Pearce study, as Pearce *et al.* themselves emphasize. The first is that Pearce *et al.* say these numbers do not take into account any property and output losses or other economic losses of land sterilization. Whether these costs play a non-negligible role, compared to health costs, cannot be answered beyond doubt by means of the comparison of existing studies, as explained in section A. If, however, a risk aversion approach (e.g. based on the empirical findings by Rocard/Smets) is applied, then it can be gleaned from what was said by the Rocard/Smets (1992) study that the additional non-health costs should be regarded as included in this risk aversion adder.

The second is that major accidents occur in other fuel cycles as well, especially coal, oil, gas and hydropower; these impacts have not been estimated in this study, "owing to the absence of a suitable literature" - ExternE seemed to be the first to make an attempt.

In his updated calculations, Pearce (1995) presented new external cost numbers, referring to new results about dose-response functions and average unit damage costs of tons of UK emissions, especially for the fossil and renewable fuel cycles. Thus, the calculations for the routine operation of the nuclear fuel cycle have also changed slightly since the 1992 study. However, the remarks about the evaluation of nuclear accidents and also the calculations themselves have not been changed since the first study by Pearce *et al.* (1992); the argument outlined above is just repeated and summarized. One additional remark found in the summary table of Pearce (1995) is that no contamination of countries other than the UK in the event of an accident is assumed.

Finally, it has to be emphasized that - although both of the approaches used by Pearce are recognized as equally fragile, they are used in the summary tables of environmental externality adders, added with and balanced against other external cost contributions - only with short footnotes about which number belongs to which procedure. There is no declared number in the summary tables that refers to an "expected value", so this appears to be at least a misleading or distorting result.

Infras/Prognos (1994)

Another study concerning external costs of current and heat generation in Switzerland (Ott *et al.*, 1994), by order of the Swiss federal offices, employs a completely different approach to dealing with the phenomenon of risk aversion. From the following explanation it seems at first glance more scientifically based than the approaches used by Pearce *et al.* However, in the Infras/Prognos study, the results are at least clearly displayed as alternative calculations to the results using the expected value. This seems more appropriate and transparent to the quick reader or user of the figures, e.g. the politician.

The summary report of the Infras/Prognos study for Switzerland is by Ott *et al.* (1994); the more detailed report for the nuclear cycle is by Masuhr and Oczipka (1994). The Prognos AG (European Center for Applied Economic Research) in Basel is the office responsible for the evaluation of nuclear accidents. It has previously been responsible for an elaborate study of "Identification and internalization of external costs of energy supply" for Germany in 1992.

The range of the Infras/Prognos study for Switzerland

The computation basis of the following mode of "risk aversion" calculation is a probability distribution of accidents for Swiss reactors, that consists of an alternative "low" and "high" probability scenario. These two scenarios are also the basis for the lower and upper results of expected values pinpointed in the description of Table 2.1.1. The basis of the lower and upper probabilities of the Infras/Prognos study should first be explained.

In Switzerland probabilistic safety analyses are carried out for 5 light water reactors of different technologies (Mühleberg, Beznau I and II, Gösgen and Leibstadt) by the HSK (Head Department for Safety of Nuclear Facilities in Switzerland). Summary results of the HSK study of the reactor at Mühleberg were taken as a basis for the calculations of source terms and probabilities by Infras/Prognos; the HSK calculations for the other reactors were not yet available at the time of the Infras/Prognos study.

These calculations, based on the HSK terms, form the "lower probability scenario" and so the "lower numbers" of the study (see Table 2.1.4). Masuhr and Oczipka (1994) note that, in order to generate this lower probability scenario, they had to condense the HSK figures in an approximate way to the source terms for the nuclear power plant at Mühleberg shown in Table 2.1.4, since the HSK summaries of the radiologically relevant nuclides of iodine and caesium were partly available only in graph form (Compare Chapter 1.1 by V. Tort including source term figures of the HSK study).

Besides the probabilities of the "lower scenario" stemming from the HSK safety assessment, Prognos added an alternative variant of probabilities. Here, the Prognos researchers multiplied the "original" lower scenario probabilities by factors from 20 (for events of lower release) up to 100 (for events of higher release) - see the column "higher scenario" in Table 2.1.4. Note that this step to generate the "higher" scenario is not supported or backed up by the original data of the HSK study.

Table 2.1.4 Possible Source Terms for Nuclear Accidents at the Nuclear Power Plant at Mühleberg for Iodine and Caesium - Lower (HSK-based) and Higher Probability Scenario

Release source terms for iodine and caesium (% of nuclear inventory)	Mean	Probability of event (events per operating year) - lower scenario (based on HSK, condensed and classified into groups by Prognos)	Probability of event (events per operating year) - higher scenario (supplemented by Prognos)
below 0.001 %	0.0005 %	1 : 200,000	1 : 10,000
0.001 % - 1 %	0.5 %	1 : 1,000,000	1 : 50,000
1 % - 10 %	5 %	13 : 10,000,000	1 : 150,000
10 % - 30 %	15 %	4 : 100,000,000	1 : 300,000
30 %	30 %	1 : 100,000,000	1 : 1,000,000
70 %	70 %	-	1 : 1,000,000

Source: Masuhr and Oczipka (1994).

This use by Prognos of much higher probabilities than covered by probabilistic safety assessments is justified in the Infras/Prognos study only by qualitative, not quantitative arguments. Masuhr and Oczipka (1994); mention that "several authors point out in this context that values used in probabilistic risk analyses cannot serve as an *absolute* measurement for actual probabilities of certain events but rather have merit as a *comparative* reliability analysis, e.g. for evaluating a new improved configuration of complex technical systems" (translation by the author). This argument is supported by a quotation by the HSK in 1987 that says risk analysis is especially suitable for identifying weak points of a facility, because the *relative risk contributions* of particular weak points can be calculated with adequate accuracy, but the result cannot be regarded as an *absolute* measurement of safety. Although a later divergent remark by HSK is conceded (HSK (1993) states they can attach much more importance to the absolute probabilities after having examined the studies pertaining to Swiss facilities), Masuhr and Oczipka (1994) argue: "The exclusive use of the mentioned probability values [i.e. the lower scenario] seems questionable, because essential points of principle in the risk analysis cannot be cleared up. The main factor of uncertainty in this case might be the impossibility of covering all possible evens." Some examples of incidents that can - according to Masuhr and Oczipka (1994) - only be described in an incomplete manner are explicitly mentioned: these are all kinds of human misconduct, the forecast of cross-linked system reactions or undiscovered manufacturing defects. Furthermore, the influence of third parties, especially sabotage, cannot be a priori evaluated by a probabilistic approach.

Self-evidently this argument cannot be denied, and it is admitted in the study that this procedure of multiplying probabilities by arbitrary factors constitutes an analytical gap with the rest of the study.

Moreover, source terms with release rates of more than 30 % are not examined by HSK. However, the "Deutsche Risikostudie Kernkraftwerke Phase B" includes higher release rates of 50 - 90 %. Therefore, in the "high probability scenario" a source term with a mean of 70 % is additionally included. Both probability scenarios are combined each with two possible dispersion scenarios (that require different levels of evacuation); these dispersion alternatives, however, only lead to a comparatively small spread of results.

Thus, the much higher "upper" result of the Infras/Prognos study (i.e. the 1.02 mECU/kWh as upper limit) compared to other recent results can be better understood when the method of its calculation by Prognos has been explained. Note that, by contrast, the "lower scenario" results of the Infras/Prognos study (backed by HSK) are compatible with the other results from probabilistic safety analyses, such as Pearce *et al.* (adjusted from risk aversion), ORNL/RFF, ExternE (CEPN), Krewitt, Hirschberg/Cazzoli and Wheeler/Hewison in Table 2.1.1.

The risk aversion concept of the Infras/Prognos study

After setting out the underlying accident probabilities, the authors of this part of the Infras/Prognos study (Masuhr, Oczipka, 1994) explain that the expected value, though somewhat plausible and therefore often regarded as the "objective" measurement of a damage calculation, cannot express the extent of possible damage. Therefore, they claim that a measurement of dispersal represents an additional factor important for individual evaluation. One dispersal measure well-known in statistics - introduced at this point in the Infras/Prognos study - is the standard deviation (the square root of the variance), given by the formula:

$$s = \sqrt{\sum_i (x_i - E)^2 * f_i}$$

with	s	=	standard deviation
	x_i	=	extent of damage for type of damage i
	E	=	expected value of damage
	f_i	=	frequency of occurrence of damage type I

There is no doubt that the standard deviation might deliver additional information and so serve as an additional parameter. But it has to be emphasized how it is used by this study: Masuhr and Oczipka, in their so-called "alternative valuation including risk consciousness", *replace* the expected value by the standard deviation. So the standard deviation is used as an alternative to the expected value as an externality adder. This leads to the following results (Table 2.1.5):

Table 2.1.5 Expected Values, Standard Deviations and Externality Adders for Nuclear Energy Calculated on this Basis in the Infras/Prognos Study

expected value (low probability scenario/ high probability scenario)	290,000 SFr - 34,000,000 SFr	174,000 ECU - 20,400,000 ECU
standard deviation (low probability scenario/ high probability scenario)	430 mn. SFr - 6,850 mn SFr	258 mn. ECU - 4,110 mn. ECU
Setting these data in proportion to the average annual electricity production of nuclear energy (for Switzerland) leads to the following parameters (covering only the component of accidents):		
externality adder, evaluation with "risk neutrality"	0.001 Rp/kWh - 0.17 Rp/kWh	0.006 mECU/kWh - 0.10 mECU/kWh
externality adder, evaluation with "risk consciousness"	1.9 Rp/kWh - 31.6 Rp/kWh	11.4 mECU/kWh - 190 mECU/kWh

1 Rp (Rappen) = 0.01 SFr. Swiss Francs converted into ECU using 1 SFr = 0.6 ECU.

Source: Masuhr and Oczipka (1994).

First, it should be acknowledged that Masuhr and Oczipka in contrast to Pearce *et al* try to found their approach on established economic theory, namely portfolio theory. This theory assumes special preferences of an individual decision-maker that can be described by utility functions that depend both on the mean (or expected value) E and on the standard deviation s of a probability distribution (and on these two parameters *only*), that is: U = f(E,s). If a person is risk-averse, the partial derivation 'U/'s is negative, that is, an increase in dispersion has to be outweighed by an increase in mean so that the decision-maker remains indifferent. If he is risk-neutral, the partial derivation 'U/'s is zero, and the utility only depends on the mean. (Note that in some literature the variance $V = s^2$ is used instead of the standard deviation as the second argument of the risk-utility function, but this does not make a difference in principal).

The primary application of portfolio theory is for models dealing with the evaluation of shares and bonds, and the question of how to hold an "optimal" portfolio. In the context of choosing equity funds, not only the average profit but also the dispersion is important for the assessment of possible losses.

There is general agreement in theoretical literature that the applicability of portfolio theory is restricted to (approximately) symmetric distributions of random variables, in the ideal case Gaussian-normal distributions (see e.g. Sinn (1989) or Schneeweiß (1991)). This premise might well be fulfilled for the expected return on investments (and in such areas of application portfolio theory surely has legitimacy) - but not for extremely asymmetric risks as is the case for nuclear energy. For random distributions of this kind, the standard deviation is of very limited use. Note that, according to portfolio theory, the decision-maker would be indifferent towards all distributions that show an equal mean and variance - no matter how much and in which direction they are asymmetric. This does not seem to be justified by reality, as can be shown easily by examples.

Thus, to refute another part of the argument in the Infras/Prognos study the approach mainly seems to be based on, the standard deviation which alone does not give any information about the "highest possible damage" and so cannot be an adequate indicator for this possible damage - especially if there are combinations of more than one damage case with different levels and probabilities.

One possible approach undertaken in (theoretical) literature is to enlarge the information of a probability distribution by adding moments of higher order as arguments to the utility function, especially the (ordinary or standardized) moment of third order that describes the skewedness of a distribution (see e.g. Sinn (1989)). Another approach, which is to take the expected utility (using the von-Neumann/Morgenstern utility functions) would appear to be a more suitable method of describing the attitude towards asymmetric risk distributions than the mean-variance model as it is used in the Prognos study. (See e.g. Krupnick, Markandya and Nickell (1993)). The problem is that taking a quadratic utility function will yield a mean variance analysis under expected utility, but such a function has many shortcomings.

Another point in the Infras/Prognos approach that does not seem to be covered by risk-utility function theory (and is thus hard to comprehend) is the following step: The argument can be generally accepted that the higher the "aversive attitude" towards risk, the more the influence of the standard deviation 's' becomes within the utility function $U = f(E,s)$. Or, put more clearly, the higher dE/ds becomes i.e. the gradient of the risk-utility indifference curves or the increase in mean necessary to "offset" an increase in dispersal. But the "extreme case" that the mean no longer has an effect at all on the utility function does not make sense, or it at least presents severe difficulties in interpreting such preferences in a meaningful way.

In the Masuhr and Oczipka approach it seems implicitly assumed that the general mean/standard deviation risk-utility function is replaced by a more tangible additive shape, of the kind:

$U = \alpha E + (1-\alpha) s$ or more generally:
$U = \alpha g(E) + (1-\alpha) h(s)$ with g, h strictly monotone functions.

Within such functions the concept is that "people whose valuation is dominated by a pronounced risk-neutrality attribute a weighting factor of 0 to the standard deviation and a factor of 1 to the mean. For persons with a strong consciousness for the risk to be incurred, however, the weighting factor of 1 is given to the standard deviation." (Masuhr, Oczipka, 1994; translated by the author).

Two arguments have to be addressed: Firstly, this extreme case (of $\alpha = 0$) would represent an extreme risk aversion by the public that is neither founded nor backed up by empirical research or diagnosis. Secondly, in the literature such a composition of mean and dispersion is found in a slightly different way - where the influence of dispersion is limited and that of the mean cannot diminish completely. See, for example, the suggestion by Hanusch (1987):

$U = E - \theta V$ with θ (the weighing factor expressing the risk attitude) **between 0 and 1**

Even if one notes that the variance V is the square of the standard deviation - so that the parameters α and θ cannot be compared directly - it is obvious that the relative influence of the dispersion parameter versus the mean has an upper bound (and must have an upper bound, to be considered plausible). In any case, it has to be added that the endeavour to get values from empirical data for the parameters in the risk-utility function, such as α or θ in the formulas above, has not succeeded up to now.

It is evident from the above that the theoretical foundation of the approach of including risk aversion by substituting the mean by the variance suffers from some severe shortcomings.

A general problem of empirical ad-hoc risk-aversion approaches: The individual and social perspective

Another point that has to be noted when examining risk-aversion approaches such as the ones expounded above is that the theory of external costs is based on the preferences and willingness-to-pay of *individuals*. From the view of the individual, however, the *maximum damage* that s/he would have to suffer in a nuclear accident - i.e. death - is in principal *no larger* than the maximum damage that can occur with alternative fuel cycles. The difference is rather that a *larger number* of individuals is affected. The transition from an individual view to a reflection of collective damage in the approaches of Pearce and Infras/Prognos makes both approaches appear questionable. One promising way forward might be to develop a new concept that distinguishes between a component "anxiety about one's own life" and another component described as "concern, anxiety or attention about large accidents where a lot of people are affected (even if happening at a great distance)". It has to be discussed if and to what extent this second endeavour has an altruistic motivation. Such a concern is certainly also guided by self-interest, e.g. social requirements. It includes especially the hostility towards drastic changes to society following these accidents. Efforts in such a direction that we have tried to outline might be more appropriate than the "classical" economic theories of behaviour under risk for explaining the observable public aversion in a consistent way,. However, to get tangible support for valuation figures such an approach would have to be accompanied by an empirical study.

Summarizing, one has to accept that the attempt to adequately incorporate risk aversion towards large accidents into valuation - and to combine theoretically complete economic theories with empirically exercisable calculations - is not yet solved satisfactorily and without doubt.

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2.2 Empirical Survey: Expert Vs Expert Risk Perception

CIEMAT (Ana Prades, Rosario Martínez, Analena Cebrián, Rebeca Meza and Rosario Solá)

A. Introduction

This chapter includes the contribution of Ciemat to the "ExternE Project Final Report on "Improvement of the assessment of severe accidents". The original Research Topics and Provisional Planning included in our first proposal were slightly modified according to the suggestions and conclusions of the project meetings (Paris, May and October, 1996).

B. Objectives & Work Programme

One of the most important concerns of the post-industrial societies lies in the specification and quantification of risk, the **Risk Assessment**. However, the efforts and resources devoted to such a goal have not avoided growing worries about both environmental conditions and the situations that potentially threaten it, generating an intense social debate about risks. In this framework, discrepancies between expert and public evaluations of risks has led to the study of **Social Risk Perception.**

Several theoretical approaches have tried to characterise the phenomenon. A reasonable conclusion of the empirical studies carried out on this issue is that all of them, experts and public, are influenced by some factors which, in turn, affect their risk perception. In particular the fact that *perception of risk among experts is also modulated by qualitative, personal and social factors*. Social Risk Perception, through the processes of Communication and Social Participation, has been shaped as a critical tool for both risk prevention and management.

Within this framework, and taking into account the ExternE general approach and pragmatic requirements, both temporal and economic, the main objective of the Ciemat research is **the identification and selection of some of the personal and social factors that modulate expert risk perception, and the attempt to obtain some empirical evidence of their relevance.**

The research tasks described below, with the correspondent work programme, were proposed for achieving this goal.

Work Programme:

1. Literature Review (including the concepts of expert vs lay risks already explored within the ExternE project)
2. Expert versus expert assessment: questionnaire and sample design
3. Data gathering
4. Data analysis
5. A comparative analysis of expert opinion according to the main dimensions of the Psychometric Paradigm
6. Final report

TASK	June	July	Aug	Sept	Oct	Nov	Dec
1							
2							
3							
4							
5							
6							

C. Methodology

To identify and select some of the personal and social factors that modulate expert risk perception and obtain empirical evidence of their relevance, a **combined methodological approach** was proposed. As a first step (Task 1) a literature review was carried out to check the personal and social factors already identified and highlighted in previous research. As a second step, a questionnaire was designed and applied to a sample of experts in an effort to obtain some empirical evidence f the real relevance of the previously identified factors (Task 2: Empirical evidence).

Task 1. Literature Review: expert vs. expert and expert vs. lay risk

Crucial conceptual elements that should be addressed

Probably the most salient element of the debate over the future of nuclear power is the *"disjuncture" between the risks of nuclear power as portrayed by experts engaged in analysis of these risks, and the perception of nuclear risks by the public, as reflected in opinion polls and other surveys."*

The community of nuclear analysts have consistently found risks from nuclear power plant accidents and from other components of the fuel cycle to be trivial. In contrast, the general public has been shown to liken nuclear power plant accident risks to risks of nuclear war. The public also appear to have ignored the expert estimates and have consistently fought for diminished reliance on nuclear power and against the location of any nuclear activity in "their backyard", irrespective of compensation offered (EUR 16521-ExternE, 1995).

Kasperson (1992) notes the disjuncture between "technical and social" perceptual analysis of hazards. The former focusing narrowly on the probability of events and the magnitude of the consequences, with "risk" defined as the multiplication of the two; the latter referring to the "qualitative properties" (newness, involuntary nature, catastrophic potential) of hazards that shape social experience and reactions. Kasperson also notes that no coherent framework for integrating technical and social aspects of risks has come forward.

Bradbury (1989) refers to technical risks as "objective" risk, and divides social risks into "psychometric risks" (which includes values and judgements of individuals) and "cultural risks" (which emphasises the social construction of risks). "Technical Risk Assessments" are dependent on numerous assumptions based on the analyst's judgement. Technical people appear to be just as vulnerable to the influence of "extraneous factors" in their judgement as any other group.

In a survey on how close different groups would be willing to live to a nuclear power plant, a coal-fired power plant and various other types of facility, Lindell and Earle (1983) found that nuclear engineers were willing to live closer to a nuclear facility than chemical engineers, but chemical engineers were willing to live closer to a coal plant than nuclear engineers. Apparently, familiarity diminishes risk even for technicians.

Fischhoff (1989) stress that the so-called objective risk estimates issued by experts contains much judgement. It is not clear whether the public can be quite so "objective" about environmental hazards, as long as they are relatively familiar ones.

According to Morgan (1993), lay people are quite capable of ordering a set of well-known hazards in terms of annual numbers of deaths. But when the same question is asked in terms of the riskiness of less-familiar hazards, they produce a different order. This difference lies at the heart of the separation between expert and lay risk assessment.

Research in this area asserts that these differences arise because lay people, unlike experts, do not define risks solely in terms of expected number of deaths. For example, Slovic (1987) has identified other attributes of risk that are important components of public perceptions:

- expert assessments of impacts conditional on an event occurring;
- some assessment of probability of the events that itself may be influenced by the way in which the public uses rules of thumb and various cognitive processes to interpret small probabilities;
- an assessment of risk attributes such as controllability, dread, voluntariness, equity (particularly inter-generational), and trust in the government or utility to deal with problems should they arise.

Given that the public's definition of risk is multifaceted, simply educating the public about expert risk will not have much effect on their overall assessment of risk unless the other components of risk are also addressed.

Kunreuhter, Desvousges and Slovic (1988) conducted various surveys to assess individual willingness-to-accept (WTA) to be located near a nuclear waste repository. They found that individuals who would accept compensation for putting up with the facility (24% of the sample) were insensitive to the amount, which varied from $ 1,000 to $5,000 per year for a period of 20 years, in the form of a credit on their income taxes. The authors conclude that the facility must meet some minimum standard of safety before people will consider trade-offs in terms of employment benefits or other compensation. The public is willing to accept expert risk assessments to a degree, but only after a set of other conditions is met that have nothing to do with assessments of probabilities and consequences.

It is often argued by the "technical" community that such risks should not be given weight in policy decisions because (a) the informed public use irrational rules of thumb in interpreting the low probabilities that experts assign to nuclear risks and (b) most of the public lacks adequate information to assess risks. These two statements are considered in turn.

(a) the informed public use irrational rules of thumb in interpreting the low probabilities that experts assign to nuclear risks

Kahneman and Tversky (1979) have extensively documented a host of cognitive processes influencing lay risk assessment. These include framing, the over-weighting of low probability events, etc. The question is whether the risk estimates that arise from these processes should then be adjusted to purge out the effects of such cognitive processes. Economic theory is clear on this point: to the extent that perceptions affect behaviour, perceptions are what matter. The WTP based on the perceptions of nuclear power risks is large indeed.

(b) most of the public lacks adequate information to assess risks

There is an on-going debate about the appropriate amount of information and understanding required of the public before their preferences are accepted as a legitimate input into public policy decisions. Opinion ranges from legitimising the given state of lay knowledge, irrespective of its depth or accuracy to relying entirely on expert opinion in cases where the good being valued is unfamiliar or complex. The previous ExternE research in this field recommended the former position (EUR 16521-ExternE, 1995). However, there may be some benefit to weighting more heavily preferences of individuals already residing in areas hosting nuclear facilities, since "familiarity" with the hazard appears to be salient in influencing perceptions. One problem with this approach is the difficulty of separating risk assessments from the influence of the economic benefits (and losses) that such facilities may bring.

<u>Expert versus expert & expert versus lay risks: the empirical evidence</u>

Numerous authors have remarked that there has, as yet, not been an attempt to weight and combine lay and expert risk in actual risk assessment.

There have been some quantitative analyses of lay risk in the literature, although they are not necessarily targeted at nuclear power plants. There are several studies of nuclear repository risks and risks posed by landfills or hazardous waste sites. While better targeted studies would be preferred, analysis by Slovic and others show that the public does not distinguish much between these type of hazards. For example, Slovic (1987), finds that the public views risks from a repository as larger than those from a nuclear power plant. The public appears to view hazardous waste sites and nuclear power plants as interchangeable in terms of risks. Another on-going study on radiological risk perception (RISKPERCOM), subsidised by the European Commission, confirmed these findings (Prades et al, 1996).

The case studies presented are based on very strong assumptions to make up for the lack of a close fit between the available literature and the questions being asked here. They are merely suggestive of possible relationships.

Use of Risk Ladders

A "risk ladder" is a graphical representation of risks (usually on log scale), ranging from certainty down to the minimum risks, with the actual risks of a variety of hazards located on the ladder to help anchor lay risk perceptions about the hazard being examined in the study. If experts are asked to rank the hazard (or else the risk from the hazard is determined outside the survey) and the lay public is asked to rank the hazard, then the ratio of the two risks (lay/expert) can be used to adjust expert risks through a simple multiplication.

McClelland, Schulze and Hurd (1990) conducted a mail survey of residents in a development located near a municipal waste landfill nominated for Superfund Priorities List located in Los Angeles. The only health problem was related to release of methane gas which causes noxious odours. No elevated levels of any chemicals have been found. The 768 residents were asked about their risk perceptions both before and after closure of the site and their responses were explained by a variety of variables. It was found that women, families with young children, distance from site (strongly correlated with odour perception) and age (younger) are strongly correlated with perceived riskiness.

The distribution of health risk perceptions from the usable responses (which may be from those most concerned) is bi-modal, expressed as deaths per 1,000,000 persons exposed. Before closure, risks were clustered at 10^{-2} and from 10^{-4} to 10^{-6}, with an average risk of 0.022. To calculate a ratio of lay risk to expert risk estimate, an estimate of expert risk is needed, which can be arrived at by assuming that it is at a minimum risk of 10^{-6} and calculating the average lay risk perception relative to this. Thus the ratio would be 2.2*104 (=0.022/ 10^{-6}). This ratio would be used for multiplication by expert-based expected deaths and injuries.

Strictly speaking, the survey results only apply to assessments of risks by the population within the affected area, which in the landfill case, was about 4,100 homes. Transferring such results to a nuclear power plant is difficult because the affected area could comprise a radius of hundreds of miles or more.

Distance-to-Acceptance Studies

A number of studies have asked respondents to provide the distance they would be willing to live from a nuclear or other type of facility, including those that may be considered "riskless" such as office buildings.

Mitchell (1980) argues that the relative distance by lay people versus nuclear engineers provides a proxy for relative differences in risk perceptions. "How close to your home could the facility be sited before you would want to move to another place or to actively protest, or would not it matter to you one way or the other how close the facility was?".

Respondents were told that each facility would be operated according to government environmental and safety regulations, whether coal, nuclear or other facilities, which is particularly advantageous because it permits a very crude estimation of net risk differentials. However, as separate polling was not done to distinguish expert from lay people it is assumed that all responses are from the lay public

Lindell and Earle have especially worked on the differences between lay/experts and between experts. Specific groups (nuclear engineers, chemical engineers, environmentalists, urbanites, science writers and people living near hazardous facilities) were asked about how close they would be willing to work or live form each of eight facilities, including a nuclear and a coal power plant.

They found different distance gradients of perceived risks that are very similar to those of Mitchell. They found that 38% of nuclear engineers are willing to live or work one mile from the NPP, while only 7% of the urban residents feel this way. Comparing responses to the coal plant, 60% of urban residents would be willing to locate 10 miles from the facility while 84% of the chemical engineers would do so.

An interesting finding is that only 47% of the nuclear engineers (a smaller percentage than for urban residents) would be willing to locate 10 miles way from the facility. A further point is that nuclear engineers would locate closer to a nuclear facility than chemical engineers while chemical engineers would locate closer to a coal facility.

To conclude it is important to stress the increasing relevance of expert risk perception as a specific research area. As said before, technical people could also be vulnerable to the influence of "extraneous factors" in their judgement.

"Expert" is not a single, unitary, concept. It includes a wide range of collectives clearly differentiated according to factors such as the area of specialisation, the kind of institution in which the knowledge is applied , etc. In research on risk perception of nuclear waste, Sjöberg (1994) found very interesting differences between experts according to factors such as:

1. *The area of specialisation*: non nuclear engineers presented a risk perception pattern half-way between that of the nuclear experts and that of the public. Discrepancies were found even between nuclear experts.
2. *The institution or company in which the knowledge is applied:* physics or engineers working at a university, for example, assess risks as higher than those who are working in private companies or public laboratories.
3. *The risks associated with their profession*: each expert minimises the risk associated with her/his own profession in comparison with the others. For example, biochemical experts underestimate the risk of genetic engineering, medical doctors those of radiotherapy, etc. Therefore, it looks like experts are not so "objective" in their assessment of the risks. They are also vulnerable to "extraneous factors", particularly to familiarity, feelings of control and their professional role.

The disjuncture between lay and experts perceptions cannot be explained in terms of lack of knowledge of the general public: experts in the same field disagree depending on where they work and how autonomous they feel.

Task 2 : Empirical Evidence: expert versus expert risk perception

In accordance with the topics identified in the literature review and with the ExternE general objectives, the goal of this task is to obtain some empirical evidence on expert versus expert risk perception relating to the following crucial conceptual dimensions:

Perceptual dimensions (attributes) according to the Psychometric Paradigm:

a) Which are the dimensions used by different experts when they perceive different risks? (academic background, professional sector of activity, familiarity with risk).

b) Basic dimensions in the utility function: subjective perceptions of probability.
"Technical risk": probability of event and magnitude of consequences (Kasperson).
Expected number of deaths of different risks.

c) Basic dimensions in the utility function: subjective perceptions of utility
Which are the *specific utilities (benefits)* that different experts relate to different risks?
(jobs, infrastructures, energy development ..)

Procedure:

1. Questionnaire Design
2. Expert sample Design
3. Expert versus expert data gathering and analysis

1. Questionnaire design

The questionnaire contains **two parts**.

The **first** (from question 1 to question 18) deals mainly with the more relevant dimensions of the psychometric paradigm, the subjective perceptions of utility and the more general attitudes.

- *Energy sources:* general attitudes, risks and benefits.

- *Risk dimensions according to the Psychometric Paradigm:* controllability, dread, voluntariness, equity, trust in government, etc.

- *Subjective perceptions of utility:* economic consequences, benefits of nuclear energy (very specific), trade off between risks and benefits.

- *Environmental attitudes:* general attitude towards the environment (cognitive, affective and behavioural dimensions) and its relationship with technology.

The **second** part of the questionnaire (from question 19 to question 29) deals with the kind of judgements contained in the so-called objective risk, the distance-to-acceptance approach, the lay/expert information needs, etc.

- *Distance-to-acceptance:* accept the installation? Who should decide its location? How would you vote on a referendum?

- *Lay/expert information needs:* what lay people should know? How should they be informed?

2. *Expert Sample Design Subjects*

The *Nuclear Energy Experts Sample* was extracted from both the Spanish Nuclear Regulatory Body (Consejo de Seguridad Nuclear - CSN) and from the Nuclear Energy Institute (ITN) of the Ciemat, the Research Centre on Energy, Environment and Technology affiliated to the Spanish Ministry of Industry.

The non-nuclear *Energy Experts Sample*, was also extracted form the Ciemat but in those Institutes not directly related with nuclear energy: Renewable Energies Institute (IER), Environmental Institute (IMA), and Conventional Energies Institute (ITEC).

It is important to underline that the Environmental Institute (IMA) is mainly devoted to environmental impacts whatever the source of the impact. Therefore, some of their experts specialise on the environmental impact of nuclear energy, others on radiological protection and so on. With regard to the Conventional Energies Institute (ITEC) it should be stressed that it is a rather new Institute and most of its experts previously belonged to the Nuclear Technology Institute.

Therefore, experts belonging to both Institutes (IMA & ITEC) represent a mid point between the Nuclear Experts and the Renewable Experts.

The *Sample of Experts From Other Technological Fields* (not related to energy), was extracted from the Telecommunications Engineering Technical School (Escuela Técnica Superior de Engineers de Telecommunications. ETSIT).

Due to the budget limitations the experts' samples were non probabilistic. However almost 50% of the total population of national experts was covered. The questionnaire was sent to **150 experts in each of the institutions** and according to the usual response rate we expected around 100 questionnaires answered in each case.

The final sample size was of 295 experts, 101 from the CSN, 92 from the Telecommunications Engineering School and 102 from the Ciemat (including sample sizes of 20-30 for ITN, IMA, IER and ITEC).

Out of the total sample, 66% were males and 33% females, covering an age range from 21 to 57 years old. The mean age was of 34 years, which could be considered a little low in comparison with one of the other studies. This is due to the inclusion of the Telecommunications Engineering Technical School students.

In order to verify the real "expertise" of the sample, the question "years of experience" was included. It is worth mentioning that the mean obtained in this variable was 9.7 years of experience. As in the case of age, the presence of Telecommunication School students has lowered this mean. Therefore the average years of experience of experts form both CSN and Ciemat is much higher than 9.7 years.

3. *Expert vs expert data gathering and analysis*

The questionnaires were distributed to the directors or managers of the different institutions. After a reasonable period two reminders were sent. The statistical package SPSS was used for carrying out the data analysis.

D. Questionnaire Results

Results will be presented according to the specific areas included in the questionnaire, as identified in the previous section.

- Energy sources
- Subjective perceptions of radiation
- Risk dimensions according to the Psychometric Paradigm
- Other relevant dimensions (Distance-to-acceptance, Lay/expert information needs)

It is important to include a preliminary and general comment about the results and the data analysis carried out in the study. Due to the expert's samples size, most of the differences between groups are statistically significant (P). Therefore, the real extent of the effect of those differences should be analysed. The Eta Square (*) correlation has been used to check the real effect of these differences between groups.

(*) Eta Square = sum of squares between groups / Total sum of squares

1. Energy Sources : Risks, benefits and general attitudes

This section presents the expert's perceptions of the risk and benefits associated with seven sources of energy as well as their general attitude towards them.

The energy sources have been ordered according to the total mean values (means of the whole sample), from the highest to the lowest. The specific mean value of each group of experts for each of the energy sources has been also included in the next columns. The statistical significance (P) and the ETA correlation are shown in the last two columns of some tables.

As far as **risk perception** is concerned, nuclear energy is considered the riskiest of all the energy sources included in the questionnaire, rated as "rather great risk". Coal, oil and natural gas are considered to have "moderate" risks, while hydropower, biomass and wind energy risk's are rate as "very small" or "non existent".

Q.2. How do you regard the risks of the different means of producing energy?

INSTITUTIONS	TOTAL Mean	CSN	ETSIT	ITN	IMA	IER	ITEC	P
Nuclear energy	4.119	3.584	4.956	3.043	3.533	5.125	3.913	.000
Coal	3.619	3.732	3.604	3.347	3.580	3.869	3.260	.546
Oil	3.479	3.178	3.879	3.391	3.161	3.750	3.454	.002
Natural Gas	3.024	2.762	3.300	3.043	2.871	3.391	2.904	.027
Hydropower	1.841	1.820	1.736	2.043	1.645	2.250	2.000	.227
Biomass	1.556	1.325	2.025	1.409	1.500	1.875	1.500	.003
Wind energy	0.941	1.020	0.696	1.217	0.871	1.250	1.045	.016

Scale from 0 = "Non existent" to 6 = "Very great".

Very significant statistical differences were found between the groups of experts when assessing the risks of these energy sources:

- experts belonging to the *IMA (Environmental Institute)* rate the risks of all energy sources below the total mean, specially those related to nuclear energy and oil.

- experts from *ITN (Nuclear Technology Institute)* also rate the risks below the general mean, in particular nuclear energy risks, in fact the lowest assessment of nuclear risks is given by this group. However, this same group rate the risks of natural gas, hydropower and wind energy above the general mean, giving the highest assessment for these risks.

- within the *ITEC (Conventional Energies Institute)*, the general trend is to value the risks below the general mean, with the exception of hydropower and wind energy.

- at the *CSN (Nuclear Regulatory Body)*, a similar trend is identified, assessing all the risks below the total mean and especially those of nuclear energy and oil. On the other hand, they stress the risks of coal and wind energy.

- conversely we find the *IER (Renewable Energies Institute),* rating all risks above the total mean, and very especially those of nuclear energy, natural gas, hydropower and biomass, in that order.

- the group at ETSI *(Telecommunications Engineering Technical School)* show a general pattern quite similar to that of the IER. This group has given the highest ratings for the risks of nuclear energy, coal, natural gas and biomass. However, regarding this last energy, the high non-response rate should be taken into account.

The same energy sources were evaluated by the experts in terms of their **benefits.**

It is clear that for the entire sample of experts the benefits are much higher than the risks in all the energy sources considered in this study. In this framework, the more profitable energies are hydropower, natural gas and nuclear energy, rated over 4 in a scale from 0 (non existent) to 6 (very great).

Q.3. How do you regard the benefits of the different means of producing energy?

INSTITUTIONS	TOTAL Mean	CSN	ETSIT	ITN	IMA	IER	ITEC	P
Hydropower.	4.639	4.717	4.630	4.739	4.871	4.000	4.565	.043
Natural Gas	4.313	4.212	4.428	4.347	4.225	4.043	4.652	.227
Nuclear energy	4.273	4.373	4.222	4.652	4.806	2.739	4.478	.000
Oil	3.848	3.656	4.097	3.826	4.032	3.130	4.181	.012
Biomass	3.477	3.238	3.585	3.173	3.333	4.478	3.722	.035
Wind energy	3.454	3.272	3.219	3.260	3.387	5.043	3.904	.000
Coal	3.130	3.380	2.695	3.347	3.258	3.043	3.500	.003

Scale from 0= "No benefits" to 6= "Very big".

As far as different expert groups are concern, the following points should be noted:

- the *IER (Renewable Energies Institute)* holds the more pessimistic view in general terms, rating more than half of the energy's benefits below the total mean. As could be expected there are two exceptions: biomass and wind energy , which are considered to have "rather great" and "great" benefits respectively.

- another group holding a quite pessimistic view is the *CSN (Nuclear Regulatory Body),* assessing the benefits of natural gas, oil, biomass and wind energy slightly below the total sample. However, their perception of the benefits related to nuclear energy and hydropower (and coal to a lesser degree) is much more optimistic than the average.

- the *ITEC (Conventional Energies Institute),* shows a more optimistic perception as far as benefits are concern. Experts working in this institute considered the benefits of all energy sources to be rather high and their mean values are above the total mean, with the only exception being hydropower.

- the group at ETSI *(Telecommunications Engineering Technical School)* shows a quite irregular pattern, ranking above the mean the benefits of natural gas, coal and biomass, and below the mean: nuclear energy, wind energy and coal.
- experts belonging to the *IMA (Environmental Institute)* show a clear trend in favour of nuclear and conventional energies while their lower benefits assessments are for the renewable energies: biomass and wind energy.

- in general terms, experts from *ITN (Nuclear Technology Institute)* assess the benefits in a very similar way to those of the IMA.

The conclusions of these results can be summarised as follows:

1. the trade-off between risks and benefits as portrayed by experts is quite favourable for all the energy sources included in this study: benefits are always rated as higher than risks.

2. the most profitable energy for the whole sample of experts is hydropower while the less profitable is coal.

3. the benefits of renewable energies are over estimated (relative to the mean) by experts belonging to the IER or ITEC and under estimated by those experts working at CSN, ITN and IMA.

4. nuclear energy benefits are highly appreciated by the CSN, ITN and IMA experts, followed by the ITEC group to a lesser degree. ETSI Telecommunications and IER clearly underestimate the benefits of this source of energy.

The last question included in this section deals with the **general attitudes** towards the seven sources of energy.

Q.1. How do you regard the different means of producing energy?

INSTITUTIONS Energy sources:	TOTAL Mean	CSN	ETSIT	ITN	IMA	IER	ITEC	P
Hydropower	4.600	4.570	4.824	4.521	4.677	3.869	4.545	.000
Wind energy	4.404	3.930	4.769	4.043	4.666	4.958	4.476	.000
Natural Gas	3.947	3.940	4.034	3.909	3.774	3.583	4.318	.095
Biomass	3.939	3.677	4.304	3.608	4.000	4.333	4.105	.026
Nuclear energy	3.204	3.620	2.820	3.956	3.580	1.583	3.318	.000
Oil	2.672	2.840	2.444	2.869	2.806	2.250	2.909	.032
Coal	2.255	2.272	2.109	2.695	2.096	2.166	2.636	.093

Scale from 0= "Extremely bad" to 6= "Extremely good".

As can be seen, the expert's **general attitude** towards hydropower, wind energy, natural gas and biomass (in that order) is rather favourable. However it is important to underline the low response rate obtained for biomass corresponding mainly to the ETSI Telecommunications group, with a non-response rate of 50%. Also 10% of the experts belonging to the CSN did not express an opinion on biomass.

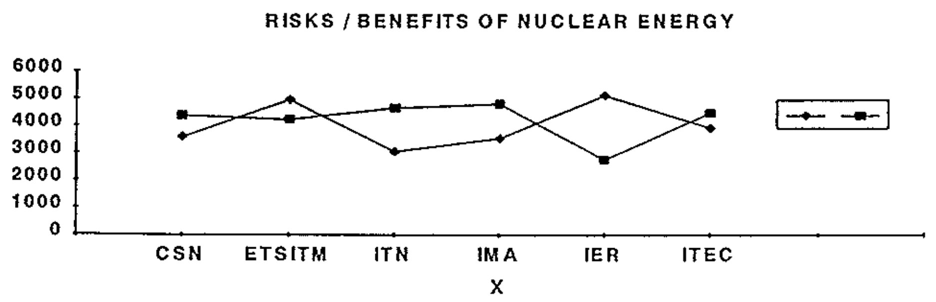
Hydropower is the energy source that has the best global assessment, at between "good" (scale 4) and "very good" (scale 5). However some differences were identified between groups. The ETSI Telecommunications group has the most favourable attitude towards hydropower, while the IER (Renewable Energies Institute) has the less favourable attitude. After hydropower, the energy with the best assessment is wind energy. As could be expected, IER and ETSI Telecommunication experts are the more optimistic ones when rating this renewable energy.

As far as the whole sample is concerned, natural gas and biomass are considered to be "good". However some differences were found between groups. ITEC holds the more favourable attitude towards natural gas, CSN and ITN are in an intermediate position while the IER assessed it below the mean of the entire expert population. IER and ETSI value biomass highly, while CSN and ITN attach less value to it.

For the whole sample, nuclear energy is ranked between a neutral and a good energy source. However, it should be stressed that very significant statistical differences were found between groups when assessing this energy source. As could be expected, the Nuclear Technology Institute has the more favourable attitude ("good"), while the IER holds the more negative opinion ("very bad")

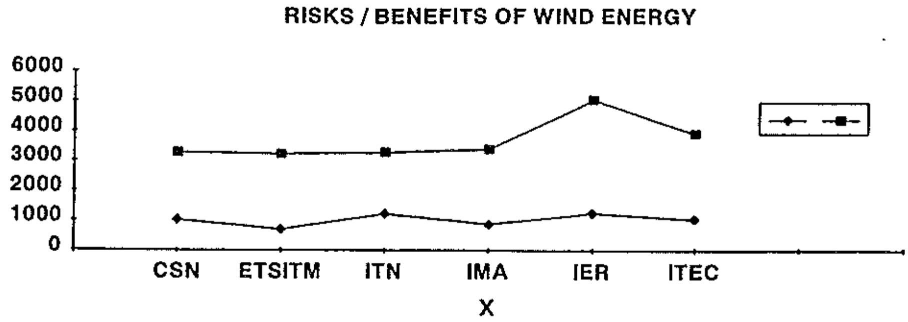
It is also worth underlining the important general agreement regarding coal and oil, which are considered to be "bad" means of producing energy.

In the graphical representations included below, both the risks and the benefits associated with two of the more relevant means of producing energy (nuclear and wind) can be easily observed.



■ Benefits ◆ Risks

Most of the experts considered the benefits linked to nuclear energy to be "good", with the exception of IER which assessed them below the mean. However, nuclear risks are also rated very high for the general sample excluding CSN and ITN experts for whom these risks are just moderate.



■ Benefits ◆ Risks

As the graphic shows, the situation is rather different for wind energy. Benefits are much more valued than risks.

In summary, nuclear energy is rated by the expert sample as both dangerous and beneficial, while for wind energy benefits are rated less but risks are also smaller than those of nuclear power.

2. Subjective Perceptions of Radiation: Trade off between risks and benefits of radiation risks.

As a preliminary statement it can be said that radioactive risks for the entire expert population are quite moderate. In a scale from 0 ("non existent") to 7 (very great"), the highest value is of 3.7 (almost moderate) while the lowest one is 2.1 ("small").

Q.5. How much are people in Spain in general at risk from the following?

	TOTAL Mean	CSN	ETSIT	ITN	IMA	IER	ITEC	NS/NC
East Europe NPP*	3.785	3.584	3.826	3.652	3.451	5.208	3.608	1
Nuclear waste	3.326	2.760	3.822	2.869	2.806	4.958	3.304	4
Spanish NPP	3.225	2.710	3.782	2.652	2.677	4.708	3.000	2
West Europe NPP	3.010	2.570	3.489	2.652	2.548	4.291	2.652	2
Nuclear arms	2.944	2.959	3.228	2.363	2.833	3.043	2.318	8
X - Rays	2.913	2.970	3.033	2.695	2.709	3.136	2.478	6
High voltage lines	2.693	2.381	3.033	2.173	2.483	3.333	2.818	8
Nuclear war	2.614	2.620	2.977	2.428	2.266	2.680	1.681	7
Food contaminated by radioactivity	2.607	2.282	3.057	2.454	2.285	3.000	2.428	15
Radon gas	2.506	2.360	3.055	2.000	2.678	3.062	2.142	72
Food irradiated to preserve it	2.203	1.531	3.223	1.210	1.680	3.611	2.277	54
Natural radiation	2.154	1.929	2.400	1.809	2.225	2.600	1.956	11
Chernobyl	2.105	1.804	2.355	2.087	1.838	2.619	2.318	11

Scale from 0 = "Non existent" to 7 = "Very great". NS/NC: N°of don't know/no answer.

* NPP = Nuclear Power Plant

Within this general context of moderate risk perception, it should be underlined that the riskiest radioactive activities are, in this order: Eastern European NPP, nuclear waste, Spanish NPP and Western NPP.

Regarding groups differences it is important to highlight that two of the expert groups are especially sensitive to radiation risks in general: IER and ETSI Telecommunications. The former is especially sensitive to NPP and nuclear waste risks. In contrast, ITN, IMA and ITEC assess most of the radiation risks below the average. The Nuclear Regulatory Body (CSN), also assess the radiation risks below the mean of the whole sample. The only risks perceived as "moderate" are those related to nuclear arms, X-rays and nuclear war.

Focusing on the four "riskiest" activities mentioned above (Eastern European NPP, nuclear waste, Spanish NPP and Western NPP), it is interesting to note that three of the groups (CSN, ITN and IMA) make an identical assessment of their risks. For all of them the riskiest hazard is from Eastern European NPP, followed by nuclear waste, Spanish NPP and Western European NPP. The three of them rate these risks to be from "moderate" to "rather small".

On the other hand, ETSI Telecommunication and IER, both show a very strong concern about radioactive risks.

The main **conclusions** of these results can be summarised as follows:

- The entire population of experts assess radiation risks to be "moderate" or "small".
- According to the expert's view the riskiest radioactive sources are: Eastern European NPP, nuclear waste, Spanish NPP and Western European NPP.
- Two institutions, IER and ETSI Telecommunication, are especially concerned about radiological risks, in particular those related to East European NPP and nuclear waste.
- For some of the experts taking part in this study, the issue of radon gas is not very well known, as it shows the highest non-response rate. The group with the highest non-response rate (50%) was ETSI Telecommunication.

The following table shows the experts perception on the **benefits** of the hazardous activities:

Q. 6. How much do you think that the following hazardous activities imply some benefits for people in Spain in general?

INSTITUTES	TOTAL Mean	CSN	ETSIT	ITN	IMA	IER	ITEC	NS/NC
X-ray diagnosis	4.429	4.710	4.077	4.521	4.548	4.260	4.500	6
Spanish nucl reac.	4.227	4.686	3.406	5.260	4.935	3.080	4.809	5
High voltage lines	3.807	3.959	3.511	4.043	3.967	3.125	4.700	9
West Euro. nuclear	2.598	2.721	2.488	3.043	2.709	1.500	3.000	11
Irradiated food	2.534	3.347	1.487	3.545	1.964	1.842	1.722	33
Natural radiation	1.544	1.178	1.654	1.500	1.689	2.545	1.578	27
Food contaminated	1.512	0.131	0.285	0.043	0.064	0.000	0.090	4
East Euro. nuclear	1.303	1.353	1.600	1.000	1.225	0.409	1.181	8
Nuclear waste	0.554	0.587	0.471	0.913	0.838	0.200	0.363	8
In home radon gas	0.520	0.406	0.681	0.590	0.428	1.071	0.350	76
Nuclear arms	0.365	0.222	0.719	0.087	0.400	0.080	0.142	8
Nuclear war	0.226	0.083	0.582	0.043	0.096	0.000	0.000	8
Effects Chernobyl	0.124	0.051	0.292	0.000	0.096	0.040	0.043	6

Scale from 0="Non existent" to 7="Very great". NS/NC: N°of don't know/no answer.

Considering expert opinion about the benefits that the mentioned hazards may imply for the Spanish population, responses ranged from "moderate", at best, to "non existent". The dispersion of the responses is much higher for the benefits than for the general risks. For the entire population of experts, the risky activities graded as the most beneficial are X-ray, followed by Spanish nuclear power plants and high voltage lines.

The benefits from Western European nuclear power plants and irradiated food where ranked at an intermediate level ("small").The benefits from natural radiation, contamination, and Eastern European nuclear power reactors were graded as "very little". Finally, nuclear waste, domestic radon gas, nuclear arms, nuclear war, and the radioactive fallout from the Chernobyl accident did not hold any benefits for the respondents.

The organisation that perceived least benefits in general was Ciemat IER, with the exception of the natural radiation and domestic radon gas ratings which were higher than those given by the other institutions.

There are very significant differences between groups when assessing the risky activities that have "moderate" benefits (X-ray diagnosis, Spanish nuclear power plants, the high voltage lines), and the risky activities having "small" benefits (Western European nuclear power reactors, and irradiated food).

Ciemat IER and Telecommunication students see less benefits than the rest of the experts, and this difference is more relevant when perceiving the benefits of Spanish nuclear power plants. The perception of the experts at the Ciemat IER are more prominently negative than the students of engineering. On the other hand, the rest of the organisations (CSN, Ciemat ITN, Ciemat IMA, and Ciemat ITEC) give valuations around the general mean, with some exceptions: CSN gives more importance than the rest of the experts to the benefits of X-rays, Ciemat ITEC rates high voltage lines more beneficially than the other Institutes, and Ciemat ITN evaluates the benefits of Spanish nuclear power plants and irradiated food higher than the other experts (including CSN).

The following aspects can be highlighted as conclusions:

- There is a specific group of radiation producing activities that hold some benefits for the Spanish population (rated as "moderately" beneficial). These are x-ray diagnosis, Spanish nuclear power plants and high voltage lines,.

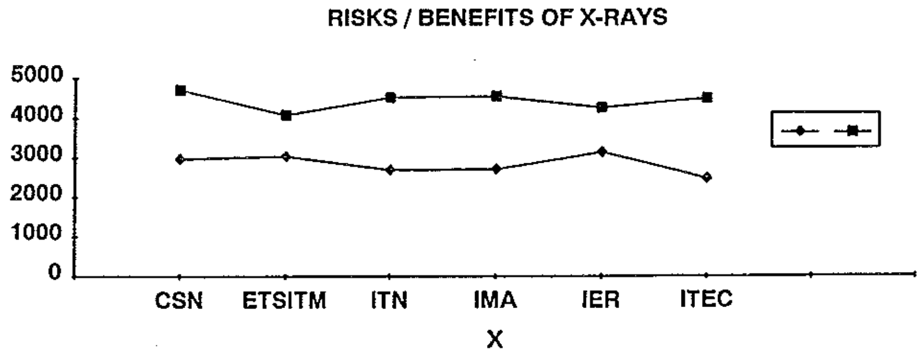
- Nuclear waste and irradiated food were considered to have "small" benefits. The remaining risks hold "rather small" or "non existent" benefits for the experts interviewed.

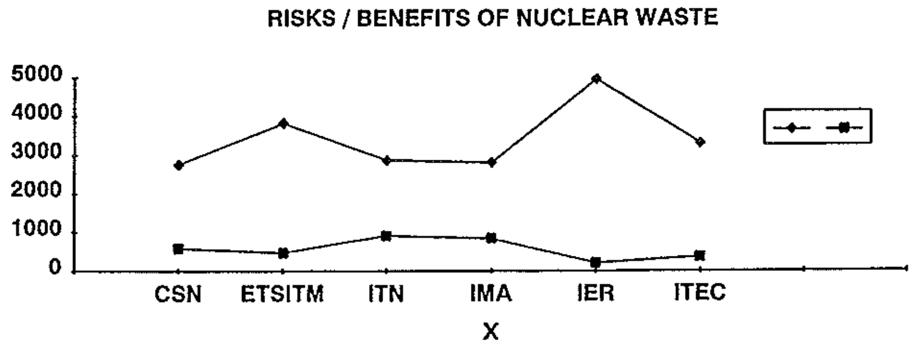
- For the radiological applications that are generally considered to have most benefits by the experts as a whole, ETSIT and Ciemat IER again show a quite sceptical attitude.

- On the other hand, some experts gave a higher grade to the benefits of radioactive activities, such as CSN for the benefits of x-rays, ITEC for high voltage lines, and ITN for Spanish and Western European nuclear power plants.

- Nuclear waste and radiation from domestic gas are consider by the experts to have no benefits for the Spanish population.

In the graphs shown below, risks and benefits perceptions towards x-rays and nuclear waste are shown, representing the range of a hypothetical radiation risk acceptability scale.





■ Benefits ◆ Risks

The graphics clearly show how familiarity with the hazard diminishes risk perception.

In conclusion it should be noted that the most beneficial radiation applications for the entire Spanish population as rated by experts are x-rays, Spanish NPP and high voltage lines. On the other hand, nuclear waste and nuclear arms are considered to have no benefits but quite big risks.

3. Perceptual Dimensions (Attributes) According to the Psychometric Paradigm

Empirical studies of individual's risk perception reveal a pattern of quite complex qualitative understandings of the term risk. Starr (1969) made a distinction between voluntary and involuntary exposure to risk, and Lawrence (1976) discussed several psychological dimensions of risk. Also, in the work of the IIASA group on attitudes towards nuclear risk during the 1970s, Otway and Von Winterfeldt (1982) reported that the acceptance of technological risks is in part based upon several qualitative dimensions. Involuntary exposure to risk, lack of personal control, lack of personal experience with the risk, benefits not highly visible, and infrequent but catastrophic accidents are some of the qualitative dimensions that may affect risk perception.

The most influential work was done by the Decision Research group in Oregon (Fischoff, Slovic, Lichtenstein, Read &Combs, 1978). Their work began by identifying the pattern of perceived characteristics of particular hazards, and through this they were able to identify the relationship between these characteristics and the perception of risk (Slovic, 1992).

The results of Slovic *et al.* indicate that ratings of the characteristics show a systematic pattern, with three important factors emerging:

The first factor was labelled by Slovic et al. as "dread" risk. This relates to judgements on matters such as uncontrollability, dread (or fear), involuntariness of exposure and inequitable distribution of risks. Hazards which rate highly for this factor include nuclear weapons, nerve gas and crime, in contrast to those that have a low rating such as home appliances and bicycles (Pidgeon, 1992).

The second factor, labelled "unknown" risk, relates to judgements about the observability of risks, whether the effects are delayed in time or not, the familiarity of the risk, and whether the risks are viewed as known to science or not. Hazards that rate highly for this factor include solar electric power, DNA research and satellites, and those that have a low rating include motor vehicles, fire fighting and mountain climbing (Pidgeon, 1992).

The third factor is related to the "number of people exposed". This relates strongly to the "dread" risk factor discussed above, because, according to Slovic "the higher a hazard scores on this factor, the higher its perceived risk, the more people want to see its current risks reduced and the more they want to see strict regulation employed to achieve the desired reduction risk" (1987, p. 283).

In his review, Slovic also notes that "expert" perceptions were found to be more synonymous with their assessments of expected fatalities, and to be less influenced by the qualitative characteristics. However, Fischoff (1990) states that the findings of his research on the judgements of a group of risk experts produced a similar factor structure to that of the lay subject groups.

The following tables include the results of the qualitative risk dimensions analysed by different groups of experts considered in this study.

"Seriousness" dimension:

Q.7.- How serious are the following hazards?

HAZARDS	MEDIA	CSN	ETSIT	ITN	IMA	IER	ITEC	P	Eta
Ozone layer depletion	4.919	4.562	5.266	4.521	4.838	5.840	4.500	.002	.26
Air pollution	4.642	4.646	4.488	4.521	4.387	5.520	4.739	.017	.22
Alcohol consumption	4.460	4.734	3.944	4.304	4.966	4.720	4.521	.001	.26
Nuclear waste	4.426	3.950	5.011	3.869	3.838	5.040	4.909	.000	.28
Spain nucl. reactors	4.162	3.949	4.433	3.913	3.774	5.000	3.909	.070	.19
Chernobyl accident	4.083	3.282	4.422	4.521	4.290	4.916	4.666	.000	.27
In home radon gas	2.708	2.505	3.468	2.238	3.000	3.000	2.368	.026	.25
Irradiated food	2.479	1.831	3.424	1.238	2.269	3.777	2.888	.000	.44
Natural radiation	2.185	1.949	2.551	1.772	2.366	2.416	1.863	.036	.21

Scale from 0="No existent" to 7="Very great".

There are two clear groups of risks differentiated according to their perceived seriousness by the experts.

The first group are risks which were evaluated as "moderate" and includes most of the risks considered, (depletion of the ozone layer, air pollution, alcohol consumption, nuclear waste, Spanish nuclear reactors, and radioactive fallout from the Chernobyl accident). The second group only includes three risks, which were evaluated as "rather small" in seriousness: radiation from in home radon gas, irradiated food and natural radiation. It is important to take into account the high number non responses in this second group because it is quite probable that this has influenced the low risk perception results.

The biggest difference between groups was found for the "irradiated food" hazard, for which telecommunication students and professionals from Ciemat IER (involved, as mentioned before, in renewable energy research) rated the seriousness as "rather small", while CSN and Ciemat ITN rated it as "very small". In between these we find Ciemat IMA and Ciemat ITEC experts, with a "small" perception of seriousness.

Other hazards with significant differences between groups were: radiation fallout from the Chernobyl accident, radioactive waste, radiation from in home radon gas, depletion of ozone layer, natural radiation and alcohol consumption.

It is important to note that there were not significant differences between groups for the perceived seriousness of hazards from nuclear reactors in Eastern Europe, Western Europe and Spain. These hazards have a mean of 4.163 for Spanish nuclear reactors, 4.744 for Eastern European nuclear reactors, and 3.875 for Western European nuclear reactors. Therefore, Spanish and Eastern European NPPs are considered more serious that Western European ones.

"Familiarity" Dimension:

The question of knowledge about different hazards is a main factor in the acceptance of a hazard. Knowledge is one of Slovic´s "unknown risk" factors. The more the hazard is known or familiar to the individual the more it will be accepted.

Q.9.- How much do you know about the following hazards?									
HAZARDS	MEDIA	CSN	ETSIT	ITN	IMA	IER	ITEC	P	Eta
Alcohol consumption	5.281	4.959	5.533	5.565	5.290	5.520	5.130	.008	.23
Spain nucl. reactors	5.123	5.800	4.477	5.478	4.935	4.666	5.087	.000	.41
Air pollution	4.837	4.571	4.788	4.869	5.258	5.360	5.000	.012	.22
Nuclear waste	4.769	5.346	4.100	4.869	5.000	4.600	4.695	.000	.34
West European NPP	4.602	5.303	3.988	4.913	4.533	3.960	4.434	.000	.35
X - ray diagnostic	4.596	5.242	4.146	4.391	4.451	4.320	4.260	.000	.34
Ozone layer depletion	4.594	4.166	4.933	4.217	4.806	5.208	4.476	.000	.28
Floods	4.594	4.393	4.955	4.347	4.322	4.920	4.304	.021	.21
East European NPP	4.220	4.676	3.755	4.434	4.333	3.800	4.173	.008	.23
Natural radiation	4.176	5.030	3.023	4.227	4.612	4.208	4.173	.000	.48
Chernobyl accident	4.132	4.760	3.494	4.652	4.451	3.320	3.913	.000	.35
Chemical waste	3.947	4.040	3.477	4.087	4.096	4.440	4.478	.010	.23
Food contamin. rad.	3.664	4.553	2.804	3.695	3.724	3.320	3.545	.000	.38
Radon gas	3.249	4.428	1.171	4.000	3.689	2.208	3.900	.000	.62
Food irradiated	3.098	4.106	1.964	3.434	3.107	2.583	3.350	.000	.46
Scale from 0="No existent" to 7="Very great".									

There are significant differences between groups for most of the hazards. The most prominent differences were found for radiation from in home radon gas. Experts from CSN and Ciemat ITN (research into nuclear technology) claim to hold a "moderate" level of knowledge about it, while on the other hand telecommunication students and Ciemat IER experts have a "very small" or "small" knowledge.

The only hazards that did not have significant differences were radiation fallout from the Chernobyl accident, East European NPP and Spanish NPP.

Considering the median response from all institutions, the highest level of knowledge was held about Spanish nuclear power plants, while knowledge of Eastern European and Western European power plants was "moderate".

CSN members have the highest knowledge for most of the hazards. Knowledge for all the hazards are said to be "moderate" or "rather great". Students of telecommunications have the fewest "rather great" knowledge ratings, although they had "moderate" knowledge of five hazards.

Knowledge of food contaminated by radiation, radiation from in home radon gas and irradiated food were rated as "rather small". These three hazards had also been rated as "small" in seriousness (see Question 7), however the level of non responses was significant and there were some differences between groups.

Another question focused specifically on the expert's knowledge about **nuclear waste**.

Q.19. Grade the level of information that you have about nuclear waste risks.	
INSTITUTIONS	*MEANS*
TOTAL	4.082
CSN	4.594
Ciemat.IMA	4.516
Ciemat ITN	4.434
Ciemat.ITEC	4.130
Ciemat.IER	3.760
ETSI Telecom.	3.321
P= .000 ; Eta= .40	
Scale from 0="No information"; to 6="Totally informed"	

There were significant differences between groups regarding knowledge of nuclear waste risks. CSN perceived itself to be the most strongly informed institution with a "rather well informed" rating. Ciemat IER and Telecommunication students were the only groups to consider themselves "moderately informed".

Psychometric dimension summary:

Q.11. How much do you agree with the following statements. A Chernobyl type accident in a nuclear reactor would:									
	MEDIA	**CSN**	**ETSIT**	**ITN**	**IMA**	**IER**	**ITEC**	**P**	**Eta**
be likely to have irreversible effects	4.889	4.666	5.181	4.695	4.322	5.520	5.000	.001	.26
be strongly feared	4.208	4.000	4.409	3.652	3.733	5.160	4.500	.002	.25
be hard to understand	3.612	4.160	3.159	3.652	3.290	3.600	3.363	.001	.26
be unjust & immoral	3.601	3.302	3.954	2.869	2.758	4.791	4.090	.000	.28
have increasing effects	3.326	3.204	3.732	2.434	2.871	3.880	3.227	.020	.22
have undetectable effects	3.266	3.616	2.602	2.863	3.366	4.083	3.727	.002	.25
be a warning that much worse injuries could happen	3.264	2.775	3.829	2.391	3.161	4.160	3.227	.000	.28
be new & unknown	2.903	3.340	2.443	3.043	2.580	2.720	3.260	.008	.23
Scale from 0="Not at all" to 6="Very much".									

There are significant differences in the above variables. The two factors that have the most significance differences are the statements that a Chernobyl type accident would be "unjust and immoral" and would be "a warning that much worse injuries can happen".

Members of Ciemat ITN and Ciemat IMA thought that a Chernobyl type accident in a nuclear reactor would be "somewhat unjust and immoral", while members of different Ciemat institutions, IER and ITEC, thought more strongly that a Chernobyl type accident would be unjust and immoral. CSN and telecommunications students held an intermediate position evaluating the accident as "moderately" unjust and immoral.

Regarding the other statement that gave significant differences; "a Chernobyl type accident in a nuclear reactor would be a warning that much worse injuries could happen", the members of CSN and Ciemat ITN only agreed with this "somewhat" while Ciemat IER agreed much more strongly.

Regarding the media for the entire population, the two statements that had a similar perception among the expert groups were that a Chernobyl type accident would be "likely to have irreversible effects" and would be "strongly feared". Both these statements were agreed with quite strongly.

"Uncertainty":

Another relevant individual dimension identified by the Psychometric Paradigm deals with "uncertainty", i.e. individual perceptions about the level of knowledge that science has about a particular question.

Two questions were formulated to evaluate the experts' perception of the level of "uncertainty" existing within current knowledge of nuclear waste matters.

Q.21. Does science know all necessary important aspects to evaluate nuclear waste management risks?	
INSTITUTIONS	*MEANS*
TOTAL	3.886
Ciemat.ITEC	4.173
Ciemat IMA	4.161
Ciemat.ITN	4.130
CSN	3.920
ETSI Telecom.	3.701
Ciemat.IER	3.560
P= .313 ; Eta= .14	
Scale from 0="Very little known"; to 6="Known in all important aspects"	

No significant differences were found between institutions with most of the experts considering actual scientific knowledge on nuclear waste to be moderate. The Ciemat, a research centre directly involved in scientific knowledge, express greater trust in this knowledge (with the exception of the Renewable Energies Institute).

Q.22. Do you believe that the most prominent experts in the area of nuclear waste hold the same opinion regarding risk evaluation?	
INSTITUTIONS	*MEANS*
TOTAL	3.415
Ciemat.IMA	4.193
Ciemat ITN	3.913
Ciemat.ITEC	3.739
CSN	3.722
ETSI Telecom.	2.802
Ciemat.IER	2.560
P= .000 ; Eta= .40	
Scale from 0="Not at all"; to 6="Yes indeed"	

On the question of whether prominent experts hold the same opinion about risk from nuclear waste, there are significant differences between groups. Those directly involved in nuclear waste are the ones with a more favourable opinion regarding expert unanimity over risk evaluation. It is important to underline that the CSN is not in charge of nuclear waste.

Conclusions

The aim of this section was to study the relevant factors effecting the perception of risks held by different groups of experts. The main findings of this research may be summarise as follows:

- The various experts questioned had a high mean perception of the **seriousness** of several hazards: depletion of the ozone layer, air pollution, alcohol consumption, nuclear waste, Spanish nuclear reactors and radioactive fallout from the Chernobyl accident. These hazards are also characterised by differences in the perception of seriousness between the different groups of experts. The biggest difference between groups corresponds to the hazard of "irradiated food".

- Prominent differences were also found in the **level of knowledge** about the hazards between groups, the hazard which had the greatest difference being "radiation from in home radon gas".

- The hazards that were perceived as among the most serious were also perceived as "rather little" known about.

- Of the institutions, CSN perceives that it maintains the highest level of knowledge about all hazards, and the Telecommunication students say they know least about the hazards. There is a tendency for experts to perceive themselves as having more knowledge about those hazards they feel more familiar with. These same hazards are, at the same time, perceived as rather serious. For example, the students perceive alcohol consumption as the hazard they know the best, rating its seriousness as moderate. The CSN perceives the depletion of ozone layer as the most serious and states a moderate knowledge.

- Regarding the different perceptions of an accident of the Chernobyl type, there is agreement that this would have irreversible effects and that it is strongly feared.

- On the matter of **uncertainty** the mean ratings of all experts on the level of scientific knowledge about nuclear waste management risks are given as moderate. Again we have to take into account the variable of "familiarity" when explaining the greater acceptance and trust of CIEMAT scientific experts in nuclear waste management.

To conclude this section the research shows the influence of the "familiarity" and "level of knowledge" factors in the acceptance of hazards. Both the familiarity and seriousness factors are relevant in assessing risk tolerability and risk management.

4. Other Relevant Dimensions:

This section includes some of the more interesting results related to the "distance-to-acceptance" approach and lay/expert information needs. Both of these questions deal again with the issues of "familiarity" (information) and "acceptability".

Distance-to-acceptance approach

Q.23. Would you accept a Government decision to carry out nuclear waste disposal in your locality?	
INSTITUTIONS	*MEANS*
TOTAL	*2.280*
Ciemat. ITN	*3.434*
CSN	*3.252*
Ciemat. ITEC	*2.913*
Ciemat. IMA.	*2.741*
Ciemat. IER	*1.000*
ETSI.Telecom	*0.925*
P= .000; Eta= .54	
Scale form 0 = no, certainly not; to 6= yes, certainly	

As can be seen, there are very significant differences between the institutions. The groups directly involved in nuclear energy show the highest level of acceptability. The Nuclear Technology Institute of the Ciemat and the CSN are the only institutions with a mean rate of acceptance above the theoretical mean (3.000). In contrast, ETSI and the Institute of Renewable Energies give a clear rejection. They would not accept in almost any circumstances this hypothetical nuclear waste disposal.

Lay/expert information needs

As mentioned before, there is an on-going debate about the appropriate level of information and understanding required by the public before their preferences are accepted as a legitimate input into public policy decisions. The perspectives range from legitimising the given state of lay knowledge irrespective of its depth or accuracy, to relying entirely on expert opinion in cases where the good being valued is unfamiliar or complex. The previous ExternE research in this field recommends erring on the former side.

A specific question (Q.20) was included with the aim of identifying the expert's general position in this debate about the appropriate amount of information that should be given to the public. It is of special interest whether differences between them appear on this issue.

As a first comment it should be said that no significant differences were found between the different institutions. Therefore, for the whole sample of experts, it is clear that informing and communicating with the public is clearly considered to be necessary. It could be said that experts are willing to improve the "familiarity" of the public with the risks they specialise in.

Q20. What amount of information should the public receive in order to comprehend the issues and problems involved in nuclear waste management:	
INSTITUTIONS	*MEANS*
TOTAL	*4.782*
Ciemat. IER	*5.200*
Ciemat. ITEC	*5.134*
Ciemat. IMA	*4.903*
ETSI: Telecom.	*4.850*
CSN	*4.613*
Ciemat.ITN	*4.3043*
P= .038 ; Eta= .20	
Scale form 0 = no information at all; to 6= all available information	

Within this general framework, it is interesting to underline the influence of the area of specialisation. The more the institution is related to nuclear energy, the less the amount of information thought necessary for public communication (Ciemat ITN and CSN). On the other hand, the less the institution is related to nuclear energy the greater the amount of information considered to be necessary for the public.

E. Conclusions: Expert vs Expert Risk Perception

1. Empirical Evidence on Expert versus Expert Risk Perception: Findings of the study.

As far as empirical evidence is concerned, clearly differentiated perceptions have been found between experts. In fact, within the whole sample of experts considered in the study, three groups of experts could be defined according to their different perceptual profiles:

Group A: This first group would include the experts belonging to the CSN (Nuclear Regulatory Body) and Ciemat-ITN (Nuclear Technology Institute), who are more directly involved in nuclear and radioactive applications.

The perceptual profile of this first group could be summarised as follows:

- This group assess the risks of most of the energy sources included in the study below the average, especially those of nuclear energy which are rated as "moderate" (lowest assessment of the whole sample). However, they assess the risks of natural gas, hydropower and wind energy above the average.

- At the same time they hold the more optimistic view regarding nuclear energy benefits, and the more pessimistic one as far as renewable energies' benefits are concerned.

- The same perceptual pattern was identified when assessing the risks and benefits of radiation uses. Risks are perceived below the average while benefits are rated above the general mean.

Group B: The second expert group would include those belonging to the Ciemat - IER (Renewable Energies Institute) and ETSI Telecommunication.

The perceptual profile of this group would be the opposite of Group A:

- Group B rates the risks of all energy sources above the total mean, and very especially those of nuclear energy, natural gas, hydropower and biomass, in that order. The ETSI students (Telecommunications Engineering Technical School), in particular, gave the highest ratings for the risks of nuclear energy, coal, natural gas and biomass.

- Regarding benefits this group holds a quite pessimistic view, rating more than half of the energies' benefits below the mean of the entire population. The only sources for which benefits are considered to outweigh risks are biomass and wind energy for the IER experts and natural gas, coal and biomass for the ETSI students.

- This group is specially sensitive to radiation risks in general and to Eastern European NPP and nuclear waste in particular.

- Group B is the one that perceive least benefits in most of the radiation source activities, including the Spanish NPP. Within the group, Ciemat - IER experts are even more prominent in their negative perception than the ETSI Telecommunication students.

Group C: A third group includes Ciemat - IMA (Environmental Institute) and Ciemat - ITEC (Conventional Energies Institute).

This group shows an intermediate perceptual profile, half-way between the two previous groups. Although both institutes can be integrated in the same generic perceptual group, it is important to stress that IMA experts are nearer to Group A (nuclear experts group) while the ITEC ones are in a more intermediate position.

- Regarding energies risk perception, IMA experts rated the risks of all energy sources below the mean of the entire sample. This was also the general trend within the ITEC, although hydropower and wind energy risks were assessed above the average.
- ITEC presented the more optimistic perception as far as energy benefits are concerned while IMA showed an specially positive assessment of nuclear energy benefits and a rather negative one of renewable energies.
- Both institutes assessed radiation risks below the average and the benefits of radiation source activities above the average.
- Again experts belonging to these two institutes were situated in the middle of the whole sample when assessing the seriousness of different risks.

2. Results of the Study & Previous Research Findings: Crucial conceptual elements that should be addressed.

As a first comment it is worth noting that the study results confirm the relevance of most of the dimensions identified as crucial in previous research. It looks quite evident now that the concept of "expert" is not a single, unitary one, but, on the contrary, it includes a wide range of clearly differentiated collectives. The three specific perceptual profiles identified within the whole sample of experts could give some support to Bradbury's (1989) argument regarding expert's vulnerability to "extraneous factors".

The significant statistical differences found between expert groups could be explained in terms of the influence of some of these "factors" or dimensions. Taking into account both the crucial perceptual dimensions previously identified and the findings of this study, the relevance of the following dimensions should be highlighted:

- **Familiarity:** As Lindell and Earle (1983) argued familiarity diminishes perceived risk even for technicians. A clear example was found when assessing the acceptability of hypothetical nuclear waste disposal in the expert's own community. Nuclear Experts (group A) were the only ones showing a level of acceptability above the average for the sample.
- **Area of specialisation:** In accordance with Sjoberg's (1994) findings about the impact of specialisation on perceptual patterns, experts in conventional energies showed a risk perception pattern half-way between that of the nuclear experts and that of renewable energy experts. Discrepancies were also found even within the nuclear expert samples, as in previous research.

- **Institution or company in which the knowledge is applied:** Experts from the university assessed risks as higher than other experts.

- **Specific risks associated with expert's profession:** Each expert minimised the risk associated with his/her own profession in comparison with the others. For example, nuclear experts give the lowest ratings for the risks of radiation uses, while renewable energy experts give the lowest ratings for the risks of biomass and wind energy, etc.

Therefore, it seems that experts are not "objective" in their assessment of risks. They are also vulnerable to "extraneous factors", particularly to familiarity and professional status.

Therefore, the disjuncture between lay and experts perceptions cannot be explained only in terms of lack of knowledge of the general public. Experts within the same field also disagree depending on where they work and how free they feel they are in their work.

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2.3 Integration of Risk Aversion in the Calculation of the External Costs of a Nuclear Accident: Expected Utility Approach

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A. Introduction

The main criticism of the monetary evaluation of the consequences associated with a nuclear accident on the basis of a probabilistic approach is that there is a discrepancy between the social acceptability of the risk and the average monetary value which corresponds in principle to the compensation of the consequences for each individual of the population affected by the accident.

It clearly appears that there is a need for integration of risk perception-risk aversion within the calculation of the external cost [1]. In this perspective, the use of the expected utility approach allows us to propose a multiplying factor according to the degree of risk aversion towards a severe accident.

The first part of this chapter presents the methodology to be applied for the calculation of this multiplying factor. The second part proposes a numerical application based on the French data for the cost of a nuclear accident.

B. General Presentation of Risk Aversion and Expected Utility Approach

The simple calculation of the cost associated with a nuclear accident based on its expected value (i.e. multiplication of the monetary consequences of the accident by the probabilities) leads usually to an underestimation of the "social" cost because it doesn't take into account the risk perception of individuals. With the introduction of the expected utility criterion, it is assumed that in evaluating risk situations, individuals replace the monetary values of the final wealth by the utility (a function) of final wealth; where this function characterises their attitude towards risk [2]. Using the expected utility approach, it is possible to calculate a multiplying factor to be applied to the cost of accident in order to reflect the individual risk perception.

Selection of a Utility Function

From the theoretical point of view, various functional forms of utility functions have been studied which reflect different attitudes towards risk. Many experimental studies have also been developed to estimate the risk aversion coefficient of individual decision makers by presenting them lotteries (i.e. a set of probabilities associated with different loss of wealth) and by letting them rank these lotteries [1, 3 to 9]. These studies usually show that the absolute risk aversion decreases with wealth. As far as relative risk aversion is concerned, they seem to support the idea of a rather constant coefficient of relative risk aversion[1]. As a consequence, two potential functional forms of the utility function emerge:

- either the utility function is logarithmic: U(W) = lnW ; implying that the coefficient of relative risk aversion is equal to unity,
- or the utility function is a power function defined by: $U(W) = \frac{1-\beta}{\beta} W^{\beta}$ with b <1. This

function exhibits positive and decreasing absolute risk aversion while the coefficient of relative risk aversion (A_r) amounts to 1-b.

Notice that fundamentally, the logarithmic utility function is a special case of the power function which is obtained by choosing b = 0. Our calculation will thus be made using the second utility function, except in the case of a relative risk aversion factor equal to 1, where the first one will be used.

If the individual is risk neutral, the relative risk aversion coefficient is zero, and the corresponding utility function is: U(W) = W

<u>*Calculation of the Multiplying Coefficient*</u>

a) The case of a binary lottery

In the expected utility approach, the evaluation of individual risk perception is made by calculating the "certainty equivalent" of a risk situation, i.e.: which level of certain wealth (without risk) would yield an individual with utility function U the same level of satisfaction as a risk situation composed of a binary lottery with a probability p of losing X% of its wealth W and a probability (1-p) of no loss. In other words, which fraction of wealth is the individual willing to lose with certainty, in order to avoid the risk situation.

The "satisfaction" given by the risk situation is evaluated by the calculation of its expected value (E(U)) which is given by the following formula:

$$E[U] = (1 - p)\, U(W) + p\, U(W - XW)$$

The "satisfaction" given by losing with certainty a fraction M of wealth in order to avoid the risk situation (certainty equivalent) is given by: U(W-MW)

In order to evaluate M, one must thus solve the following equation:

$$E[U] = U(W - MW)$$

1 The terms 'absolute risk aversion' and 'relative risk aversion' are tied to the nature of the lottery. Absolute risk aversion applies to additive lotteries that are expressed in monetary units while relative risk aversion applies to multiplicative lotteries in rates or fraction. In our case, the monetary consequences of accidents will be expressed in terms of percentage of loss wealth. We will thus use the relative risk aversion coefficient (Ar). For a given utility function, this coefficient is obtained by the following formula: Ar = - W . [U"(W)/U'(W)].

- <u>If the individual is risk neutral</u> (U (W) = W), the equation is:

E[U] = (1-p) W + p (W-XW) = U(W-M_NW)

where M_N is the "willingness to pay" of a risk neutral individual to avoid the lottery.

Solving the equation gives:

E[U] = W (1 - p X) = W - M_N W

<=> $\boxed{M_N = pX}$

- <u>If the individual is risk averse</u> (U(W) = (1- b/b) $(W)^b$) the equation is:

$$E[U] = (1-p)\left(\frac{1-\beta}{\beta}\right) W^{\beta} + p\left(\frac{1-\beta}{\beta}\right)(W - XW)^{\beta} = U(W - M_A W$$

where M_A is the "willingness to pay" of a risk averse individual to avoid the lottery.

Solving the equation gives:

$$(1-p)\left(\frac{1-\beta}{\beta}\right) W^{\beta} + p\left(\frac{1-\beta}{\beta}\right)(W - XW)^{\beta} = \left(\frac{1-\beta}{\beta}\right)(W - M_A W)^{\beta}$$

$$\Leftrightarrow \quad (1-p)W^{\beta} + pW^{\beta}(1-X)^{\beta} = W^{\beta}(1-M_A)^{\beta}$$

$$\Leftrightarrow \quad (1-p) + p(1-X)^{\beta} = (1-M_A)^{\beta}$$

$$\Leftrightarrow \quad 1 - M_A = \left[1 - p + p(1-X)^{\beta}\right]^{\frac{1}{\beta}}$$

$$\Leftrightarrow \quad \boxed{M_A = 1 - \left[1 - p + p(1-X)^{\beta}\right]^{\frac{1}{\beta}}}$$

Multiplying coefficient:

The external costs of an accident are calculated assuming risk neutrality. Thus, in order to take account of risk aversion in this calculation, the external costs must be multiplied by the following coefficient which corresponds to the ratio between the willingness to pay to avoid an accident with and without risk aversion:

$$\boxed{\frac{M_A}{M_N} = \frac{1 - \left[1 - p + p(1-X)^{\beta}\right]^{\frac{1}{\beta}}}{pX}}$$

b) Case of a lottery with n "states of the world"
When the risk situation is characterised by n states of the world, i.e. a set of probabilities $(p_1, p_2,\ldots, p_i,\ldots, p_n)$ associated with the losses of wealth $(X_1, X_2,\ldots,X_i,\ldots,X_n)$ with $\sum_{i=1}^{n} p_i = 1$, the calculation of the certainty equivalent in the case of a risk averse individual is given by:

$$E[U] = \frac{1-\beta}{\beta} \cdot \sum_{i=1}^{n} p_i \left(W(1-X_i)\right)^{\beta} = \frac{1-\beta}{\beta} \cdot W^{\beta} \cdot (1-M_A)^{\beta}$$

Which leads to:

$$\boxed{M_A = 1-\left[\sum_{i=1}^{n} p_i \; (1-X_i)^{\beta}\right]^{\frac{1}{\beta}}}$$

For a risk neutral individual, we have:

$$\boxed{M_N = \sum_{i=1}^{n} p_i X_i}$$

The multiplying coefficient to be applied to the mathematically expected value of the cost of an accident is given by:

$$\boxed{\frac{M_A}{M_N} = \frac{1-\left[\sum_{i=1}^{n} p_i \; (1-X_i)^{\beta}\right]^{\frac{1}{\beta}}}{\sum_{i=1}^{n} p_i X_i}}$$

C. Numerical Application

<u>*States of the World*</u>

- **Identification of the population**

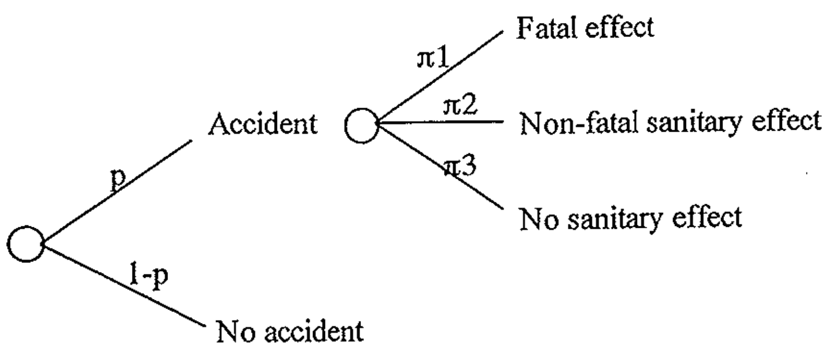
The total population of the country is assumed to be equal to 56 millions of inhabitants. This population is sub-divided into two areas:

- **Local**, i.e. area around the nuclear power plant (< 100 km) where the inhabitants may be evacuated and relocated. It is assumed that 2 million inhabitants are living in this area. The distinction between relocated and non-relocated people will be made in the evaluation of the cost. The number of people concerned in each case will depend on the chosen scenario of accident.

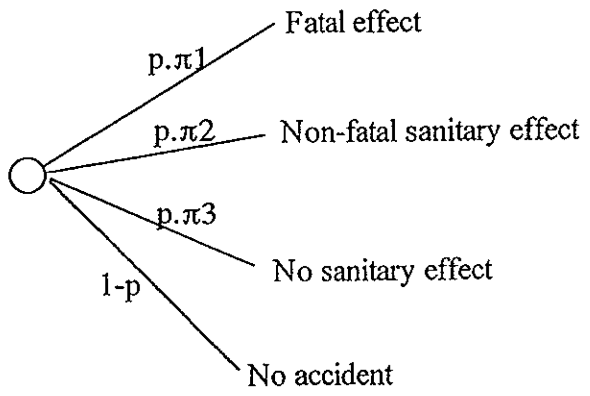
• - **Regional**, i.e. area farther away from the power plant (>100 km). 54 million inhabitants are concerned.

• Identification of the states of the world

In each area, it is possible to distinguish four "states of the world" depending on the potential health consequences, represented by the following lottery:



Which corresponds to[2]:



The probability of each consequence depends on the chosen scenario of accident. The following tables give for each area, the calculation of the probabilities corresponding to the French scenario, called ST21 (which corresponds to a release of about 1% of the core)[3] [10]. The probabilities of fatal and non-fatal effects are derived from the number of effects expected divided by the size of the population of each area.

2 This combination of probabilities comes from the hypothesis of independence of the events, used in the expected utility theory.

3 The other scenarios are presented in Appendix 1

Table 1: Number of Fatal and Non-Fatal Effects

Area	No. of fatal cancers	No. of severe hereditary effects	No. of non-fatal cancers	No. of early diseases	Total no. of fatal effects	Total no. of non-fatal effects
Local	410	82	984	2	492	986
Regional	2505	501	6012		3006	6012

Table 2: Individual Probability of Fatal, Non-Fatal and No Effect

Area	Number of individuals (million of inhabitants)	Probability of fatal effects (p_1)	Probability of non-fatal effects (p_2)	Probability of no effects (p_3)
Local	2	2.46 E-04	4.93 E-04	9.9926 E-01
Regional	54	5.57 E-05	1.11 E-04	9.9983 E-01

Table 3: Individual Probability for Each State of the World

Area	Probability of accident (p)	Probability of accident and fatal effect ($p.p_1$)	Probability of accident and non-fatal effect ($p.p_2$)	Probability of accident and no effects ($p.p_3$)	Probability of no accident (1-p)
Local	1.9 E-06	4.7 E-10	9.4 E-10	1.9 E-06	9.99998 E-01
Regional	1.9 E-06	1.06 E-10	2.12 E-10	1.9 E-06	9.99998 E-01

- **Monetary consequences**

The calculation of the monetary consequences is mainly based on the economic module of COSYMA with additional considerations on indirect costs. On this basis, five main categories of cost can be distinguished:

- Food ban costs
- Evacuation and relocation costs
- Indirect costs
- Fatal effect costs
- Non-fatal effect costs

For the calculation of the aversion multiplying coefficient, it is necessary to express them as individual cost.

a) Food ban costs

The food ban costs are borne by individuals living in both local and regional areas.

Table 4: Calculation of Individual Food Ban Costs

Area	Total food ban costs (MECU)	Number of individuals (million of inhabitants)	Individual food ban costs (MECU)
Local	330.70	2	1.65350 E-04
Regional	5820.00	54	1.07778 E-04

b) Evacuation and relocation costs

These costs concern only the local area and within this area, only the number of people who are supposed to be evacuated and relocated.

Table 5: Calculation of Individual Evacuation and Relocation Costs

Area	Total evacuation and relocation costs (MECU)	Nb of evacuated and relocated people	Individual evacuation and relocation costs (MECU)
Local	98.1	9800	1.00102 E-02

c) Indirect costs

The indirect costs, borne only by local people, are assumed to be equal to 25% of the total local direct costs. The total direct costs are equal to the sum of the health effect cost, the food ban costs and the evacuation/relocation costs. The total health effect costs are derived from the number of fatal effects and non-fatal effects. The cost of a fatal effect is assumed to be equal to 2.6 MECU (monetary value of life used in the ExternE study [1]). The cost of a non fatal effect is assumed to be equal to 0.25 MECU.

Table 6: Calculation of Total Health Effects Costs

Area	Total number of fatal effects	Total number of non-fatal effects	Total health effects costs (MECU)
Local	492	986	1525.7

Table 7: Calculation of Individual Indirect Costs

Area	Total direct costs (MECU)	Total indirect costs (25% of total direct costs) (MECU)	Number of individuals (million of inhabitants)	Individual indirect costs (MECU)
Local	1954.5	488.63	2	2.4431 E-04

- **Summary of data**

In order to calculate the multiplying coefficient to be applied to the cost of the accident, it is necessary to express the various costs as a percentage of individual loss of wealth. As, in the external cost study, the evaluation of the loss of individual wealth associated with the nuclear accident is based on the monetary value of life, as well as the loss of property, we assume that the individual wealth of an individual is made of these two components:

- the monetary value of life (2.6 MECU) [1],
- the average individual financial wealth (0.07 MECU)[4].

The following tables summarise for each area, the total individual cost corresponding to each state of the world, the associated loss of wealth and probabilities. The states of the world need to be separated into three groups of individuals, each group bearing a different set of costs:

- 1st group: local and relocated,
- 2nd group: local and not-relocated,
- 3rd group: regional.

Table 8: Total Individual Costs in Each State of the World

Sub-Group	States of the world	Individual cost of health effects (MECU)	Individual food bans costs (MECU)	Individual evac. + relocation costs (MECU)	Individual indirect costs (MECU)	Total individual costs (MECU)
Local relocated	Local relocated + fatal effect	2.6	1.6535 E-0	1.0010 E-02	2.4431 E-0	2.6104
	Local relocated + non-fatal effect	0.25	1.6535 E-0	1.0010 E-02	2.4433 E-0	2.6042 E-0
	Local relocated + no health effect	0	1.6535 E-0	1.0010 E-02	2.4431 E-0	1.0420 E-0
Local not relocated	Local not relocated + fatal effect	2.6	1.6535 E-0	-	2.4431 E-0	2.6004
	Local not relocated + non-fatal effect	0.25	1.6535 E-0	-	2.4431 E-0	2.5041 E-0
	Local not relocated + no health effect	0	1.6535 E-0	-	2.4431 E-0	4.0966 E-0
Regional	regional + fatal effect	2.6	1.0778 E-0	-	-	2.6001
	regional + non-fatal effect	0.25	1.0778 E-0	-	-	2.5011 E-0
	regional + no health effect	0	1.0778 E-0	-	-	1.0778 E-0

4 The value of the average individual financial wealth is based on French data [11]:
- private capital per household: 170 KECU ;
- average number of persons per household: 2.5 persons

Table 9: The "Lotteries" Associated with a Nuclear Accident (ST21 Scenario)

Sub Group	States of the world	% wealth loss	Probability
Local	Local relocated + fatal effect	97.77%	4.6740 E-10
	Local relocated + non-fatal effect	9.75%	9.3708 E-10
	Local relocated + no health effect	0.39%	1.8986 E-06
	No accident	0%	9.99998 E-0
Local no relocated	Local no relocated + fatal effect	97.39%	4.6740 E-10
	Local no relocated + non-fatal effect	9.38%	9.3708 E-10
	Local no relocated + no health effect	0.02%	1.8986 E-06
	No accident	0%	9.99998 E-0
Regional	regional + fatal effect	97.38%	1.0577 E-10
	regional + non-fatal effect	9.37%	2.1153 E-10
	regional + no health effect	0.004%	1.8997 E-06
	No accident	0%	9.99998 E-0

Calculation of the Multiplying Coefficient

- **Selection of a risk aversion coefficient**

The empirical studies performed to estimate the relative risk aversion coefficient usually propose a coefficient approximately between 0.5 and 2.5 [3 to 6]. However, two very recent studies (H. Levy [7] and D. Blake [8]) propose some values much higher than this. These authors have derived the decision makers' utility functions from observed (portfolio) choices. In his paper, Levy used portfolio choices made by MBA students in an experimental study replicating conditions of the stock market. More recently, D. Blake derived coefficient of relative risk aversion from "real world" asset composition of the portfolio of English households. The level of the risk aversion coefficient (A_r), resulting essentially from Blake's study seems to be much higher than those obtained in previous studies based on similar data sets. His paper, as well as a previous one by Mehra and Prescott [9] produces a coefficient that can be as high as 47!

In our opinion, the Blake study, because of its methodology, probably overestimates the true value of A_r. Indeed, the value of A_r he obtains is consistent with high equity premium observed on stock markets. However, such a high premium may result from sources other than a high coefficient of relative risk aversion. In fact, when they make portfolio choices, decision makers are aware that they bear many other risks than the ones attached to their portfolio (accident, health, and so on...). Because of these other "background" risks, they are probably very conservative towards portfolio risks so that the high equity premium results from two factors (and not from a single one): background risk and the degree of relative risk aversion. Implicitly in his paper, Blake explains the equity premium exclusively through the level of A_r, which is thus likely to be overestimated.

In the case of a nuclear accident, the individuals are facing a lottery which is characterised by a high probability of no loss, and small probabilities of great loss (up to 98 % of the initial wealth). It is then difficult to directly apply the values of a risk aversion coefficient which have been observed on the stock market, where the amount of possible loss is far less. In fact, when applying a risk aversion coefficient greater than 2.5 to the "nuclear accident lottery", to take into account the individual risk aversion leads to absurd values of the certainty equivalent: the individuals would be willing to pay nearly the total cost of the consequences of the accident in order to avoid it, i.e. approximately all their wealth (the values of M_A are rising exponentially with the increase of the relative risk aversion coefficient).

Therefore, according to the previous studies on risk aversion, we propose to retain a value of 2 for the relative risk aversion coefficient. The utility function is then:

$$U(W) = \frac{1-\beta}{\beta} W^{\beta}, \text{ with } \beta = 1 - A_r = -1$$

$$\Rightarrow \boxed{U(W) = -2\,W^{-1}}$$

- **Calculation of the multiplying coefficient**

In order to obtain a total multiplying coefficient, it is first necessary to calculate the coefficient M_A (percentage of wealth that a risk averse individual is willing to lose with certainty in order to avoid the accident) and M_N (percentage of wealth that a risk neutral individual is willing to lose with certainty in order to avoid the accident) for each group of individuals and then to calculate the ratio of the sum of these coefficients weighted by the size of the population of each group.

If we call M_{A1}, M_{A2}, M_{A3} and M_{N1}, M_{N2}, M_{N3} the respective coefficient of the first, second and third group of individuals, and N_1, N_2, N_3 the population of each group, the total multiplying coefficient to be applied to the cost of the nuclear accident is obtained by the following formula:

$$\boxed{M = \frac{N_1.M_{A1} + N_2.M_{A2} + N_3.M_{A3}}{N_1.M_{N1} + N_2.M_{N2} + N_3.M_{N3}}}$$

The lottery of the first group (local and relocated individuals) concerns N_1 = 58400 individuals and is characterised by the following set of consequences and probabilities:

States of the world	% wealth loss (X_i)	Probability (p_i)
Local relocated + fatal effect	97.77%	4.6740 E-10
Local relocated + non-fatal effect	9.75%	9.3708 E-10
Local relocated + no health effect	0.39%	1.8986 E-06
No accident	0%	9.99998 E-01

The lottery of the second group (local and no relocated individuals) concerns N_2 = 1 941 600 individuals and is characterised by the following set of consequences and probabilities:

States of the world	% wealth loss (X_i)	Probability (p_i)
Local not relocated + fatal effect	97.39%	4.6740 E-10
Local not relocated + non-fatal effect	9.38%	9.3708 E-10
Local not relocated + no health effect	0.02%	1.8986 E-06
No accident	0%	9.99998 E-01

The lottery of the third group (regional individuals) concerns N_3 = 54 million individuals and is characterised by the following set of consequences and probabilities:

States of the world	% wealth loss (X_i)	Probability (p_i)
regional + fatal effect	97.38%	1.0577 E-10
regional + non-fatal effect	9.37%	2.1153 E-10
regional + no health effect	0.004%	1.8997 E-06
No accident	0%	9.99998 E-01

The following tables give the value of M_A (percentage of wealth that a risk averse individual is willing to lose with certainty in order to avoid the accident) and M_N (percentage of wealth that a risk neutral individual is willing to lose with certainty in order to avoid the accident) for each group of individuals. The calculation of the multiplying coefficient for other values of the risk aversion coefficient, and other accident scenarios are presented in Appendix 1.

Table 10: Calculation of Multiplying Coefficient for Each Group of Individuals

	First Group: Local and relocated	Second Group: Local and not relocated	Third Group: Regional
Size of the population (N)	58400	1 941 600	54 E+06
$M_A = 1 - \left[\sum_{i=1}^{3} p_i \ (1 - X_i)^{-1}\right]^{-1}$	2.802 E-08	1.785 E-08	4.033 E-09
$M_N = \sum_{i=1}^{3} p_i X_i$	7.958 E-09	8.344 E-10	1.995 E-10
$\frac{M_A}{M_N} = \frac{1 - \left[\sum_{i=1}^{3} p_i \ (1 - X_i)^{-1}\right]^{-1}}{\sum_{i=1}^{3} p_i \ X_i}$	3.5209	21.3968	20.2172

Table 11: Calculation of National Multiplying Coefficient

	Result
$M_A = N_1.M_{A1} + N_2.M_{A2} + N_3.M_{A3}$	2.5410 E-01
$M_N = N_1.M_{N1} + N_2.M_{N2} + N_3.M_{N3}$	1.2858 E-02
$M = \frac{N_1.M_{A1} + N_2.M_{A2} + N_3.M_{A3}}{N_1.M_{N1} + N_2.M_{N2} + N_3.M_{N3}}$	**19.7623**

Calculation of the External Cost of the Accident per KWh

The external cost of the accident is calculated in three steps:

- Calculation of the "expected" value of the cost of accident. This value, expressed in MECU per reactor year, is obtained by multiplying the total cost of the accident by the probability of occurrence of the accident (in the case presented above, this probability is equal to 1.9E-06 per reactor.year).

- Calculation of the external cost of the nuclear accident, expressed in mECU per KWh. It is assumed here that the annual production of electricity of a reactor is equal to 7.6 TWh [10]. The external cost is then obtained by dividing the expected value by this annual production.

- Calculation of the external cost of accident including risk aversion. This value is obtained by multiplying the external cost by the multiplying factor calculated previously (M_A/M_N = 19.7623 in this case).

The results are presented in Tables 12 and 13.

Table 12: Total Costs of the Nuclear Accident (ST21 Scenario)

Cost category	Local Costs (MECU)	Regional Costs (MECU)	Total Costs (MECU)
Food-ban	330.70	5820.00	6150.70
Evacuation and relocation	98.10	-	98.10
Indirect costs	488.65	-	488.65
Fatal effects	1279.20	7815.60	9094.80
Non-fatal effects	246.50	1503.00	1749.50
Total	**2443.15**	**15138.60**	**17581.75**

Table 13: External Cost of the Nuclear Accident

Total Cost (MECU)	**"Expected total cost"** (Total cost x probability of accident) (MECU/reactor.year)	**External Cost of accident** ("expected" total cost / 7.6) (mECU/KWh)	**External Cost of accident including risk aversion** (external cost x multiplying coefficient) (mECU/KWh)
17581.75	0.0334	0.0044	**0.087**

The total external cost of the nuclear fuel cycle calculated with the French reference and without accident was estimated at 2.5 mECU/KWh (without discounting). The external cost of the accident taking into account risk aversion is equal to 0.087 mECU/KWh, and represents 3.4 % of this total external cost. (Without risk aversion, the external cost of the accident would represent approximately 0.18 % of the total cost of the nuclear fuel cycle).

D. Conclusion

This paper shows that the calculation of the external cost of a nuclear accident integrating risk aversion is feasible by applying expected utility approach. One of the advantages of this approach is the availability of experimental data concerning risk aversion coefficient. Although a huge range of values has been published for this coefficient, mainly based on the analysis of financial risks, it seems reasonable to adopt a risk coefficient around 2 for the specific case of a nuclear accident. This leads to an estimated multiplying coefficient approximately equal to 20 to be applied to the external cost of a nuclear accident corresponding to a release of about 1 % of the core. In this case, the external cost of the nuclear accident is 0.087 mECU/KWh (i.e. about 3.4% of the total external costs of the nuclear fuel cycle), instead of 0.0044 mECU/KWh without taking into account risk aversion.

Such a methodology could also be applied to the evaluation of the cost of other severe accidents. For this purpose, it is necessary to identify the different "states of the world" describing the risk situations, as well as to delineate the homogeneous groups of individuals facing the same risk situations.

Finally, specific attention could also be paid to the social dimension of risks associated with severe accidents. Indeed, in the case of a nuclear accident, two types of risk can be distinguished:

- the first type corresponds to the various effects of the accident (food-ban costs, relocation and evacuation costs, indirect costs, health effects costs) which affects each individual differently;
- the second type concerns the occurrence of the nuclear accident itself which is imposed on the whole population.

In fact, the first type of risk is considered to be "diversifiable" (in principle, individuals can cover the risk by an insurance contract) while the second one is not. In this analysis, no distinction has been introduced, although preliminary studies in this field tend to prove that the social risk should be higher in the presence of "non-diversifiable" risks than with "diversifiable" ones [12]. More emphasise should be devoted to this topic in the future.

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Appendix 1: Calculation of Multiplying Coefficient for Scenarios ST2, ST21, ST22 and ST23 with Sensibility Analysis on the Value of the Risk Aversion Coefficient

Hypothesis:

Scenario ST2:
- 10 % of total core released
- p = 1.9 E-06

Scenario ST21:
- 1 % of total core released
- p = 1.9 E-06

Scenario ST22:
- 0.1 % of total core released
- p = 1.9 E-06

Scenario ST23:
- 0.01 % of total core released
- p = 1.81 E-06

Summary Table :

The Multiplying Coefficient According to Risk Aversion Coefficients and Accident Scenarios

Scenarios	Risk aversion coefficient (a)				
	0.5	**1.2**	**2**	**2.5**	**3**
ST2	1.3814	3.3806	20.7885	86.6840	404.9609
ST21	1.3657	3.2749	19.7623	81.6941	378.4633
ST22	1.3750	3.3316	20.2047	83.5069	386.4885
ST23	1.3108	2.932	16.9085	69.3341	320.2172

2.4 The Economics of Risk and Uncertainty and the Valuation of Severe Accidents

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A. Introduction

Previous Work on Economic Valuation of Large Accidents

The assessment of the nuclear fuel cycle within the ExternE project has followed an approach which may be called "expert expected damage" (EED), postulating that the social cost of an accident with probability p and estimated consequences of XM (in money terms) amounts to:

$$D = pXM. \qquad (1)$$

where the cost of the accident in case it occurs is usually seen as a percentage X of money income M.

However, in Chapter 17, Part II of the ExternE Methodology[1] (henceforth "Ch.17" for simplicity) it was noted that this approach can only be regarded as an *ex-post* valuation of such social costs, or is appropriate in the special case where individuals and the community as a whole are *risk-neutral* with respect to the consequences of the accident. On the other hand, this is not the general case, as stressed in recent literature on valuation in an uncertain world[2]. Therefore, Ch. 17 undertakes an exercise consisting of two parts:

(i) the mainstream approach to decision making under uncertainty, i.e. Expected Utility Theory (Eu) is adopted, so that damage is valued *ex-ante* as the amount which makes the individual indifferent between giving up a certain amount of money W (out of income M) and facing the risky lottery, summarised by its expected utility:

$$\Sigma\, p_i\, v\,(z_i) = v\,(M-W) \qquad (2).$$

W can therefore be interpreted as willingness to pay to avoid facing the risky lottery of living with a nuclear plant;

(ii) the introduction of risk-averse decision-making may not however be regarded as an appropriate description of lay people's perception of the hazards of nuclear power, the valuation of which is the goal declared by Ch. 17. It is underlined that several studies have estimated how people may replace expert assessment of accident probabilities by their own. Therefore, following Viscusi (1989) and Smith (1992), the latter part of Ch. 17 redefines probability p as a weighted average of expert and lay assessment of chances of the adverse event. Ratios of ex-ante to ex-post social cost values vary accordingly.

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[1] largely based on an article by Krupnick, Markandya and Nickell (1993)

[2] See e.g. Freeman (1993), chp. 8.

Outline of Appraisal and Extension of Previous Work.

The present paper starts from results achieved in Ch. 17, but introduces a number of amendments, for theoretical and empirical reasons. Further, a new modelling strategy will be suggested to bring treatment of this topic more in line with the state of the art in decision making under uncertainty as well as with general methodological principles of the ExternE project.

In section B, results of Eu approach as developed in Ch. 17 are recalled, with a few adjustments. In particular, we consider estimates of the consequences of a large nuclear accident as assessed by CEPN for the EC nuclear fuel cycle study (as implemented for the French reference case).

In section C, criticisms of the Eu approach will be summarised and some of its best known generalisations will be outlined, with particular attention to their empirical specifications arising from a small but expanding stream of experimental results. In particular, two approaches will be selected (disappointment aversion and expected utility with rank-dependent probability) for valuation which follow the same approach as Ch. 17 but for the replacement of Eu. Simulations results will also be provided.

Section D is devoted to discussion of the normative value of alternative approaches to expected utility, as they have often been criticised as rationalisations of irrationality and poor information, while it may be argued that they represent the closests approximation to actual preference structures which are peculiar to nuclear power perception. In this respect, a way out of conceptual difficulties may be represented by the alternative already suggested in Ch. 17 (prospective reference theory), which is particularly appealing for the valuation of a large accident with low probability, since it allows for gradual adjustments of probability perception by subjects at risk. However we think that more empirical work is needed for a sensible application of this promising approach to the nuclear accident problem.

Finally, section E explores two additional issues which (we believe) should be addressed in order to develop a more consistent modelling strategy for the estimation of social costs of severe nuclear accidents. In our view, a serious problem with the approach of Ch. 17 and its adaptations pursued in the previous section lies in the direct use of individual decision making procedures at social level, which is not consistent with the general methodology of welfare economics, as accepted by the ExternE project. Whatever theory is used (Eu or one of its generalisation), it should be applied at the individual or household level, upon consideration of the "lottery" (the risky situation) actually faced by each representative subject. Aggregation could only be carried out after individual WTP's are calculated, in order to estimate total social cost of the feared event.

Moreover, the modelling of the individual exposed to the consequences of a severe accident is inadequate as (s)he actually faces a multistage lottery, being uncertain about (a) whether or not the accident will occur and, if this is the case, to a certain extent about (b) the final consequences of this (e.g. whether or not he or she will be hit by serious disease). Acknowledgement of this situation might also constitute the basis for extension of valuation under risk to other fuel cycles.

B. Expected Utility Approach Within the ExternE Framework.

In Ch. 17, equation (2) above is solved for W. In the actual implementation the argument of the (indirect) utility function z_i amounts to income M in the case of no accident (with probability 1-p), and to M(1-X) in the case of an accident A* occurring, with probability p:

$$p\ v\ (M-MX) + (1-p)\ v\ (M) = v\ (M-W) \tag{2'}$$

Some assumptions concerning the shape and parameters of the utility function and values of the accident X (as a percentage of income M in the affected area) are used in order to solve (2') for the ex-ante valuation W, while the values of X and p are taken from the U.S. nuclear fuel cycle study. Results are given in terms of the ratio W/D, where D is the ex-post valuation given by (1). Two utility functions are suggested:

I: $V=(M(1-W))^b/(1-b)$
II: $V=-\exp(-bM(1-W))$

We deemed them to be sufficiently representative, although slightly different specifications could also be used. In particular function I is not exactly the same as used in Ch. 17 but yields exactly the same results for our decision problem. The version chosen as I is more theoretically consistent and is quite popular among uncertainty analysts as the constant relative risk aversion (CRRA) function. With such functions, the relative risk aversion parameter is given by:

$r=-V''M/V'=1-b$
$r=-V''M/V'=b(1-X)M$

The relative risk aversion parameter chosen was 2.5, an average value found in the evidence provided by analysis of financial markets (Cohn, *et al.*, 1975; Friend and Blume, 1975; Morin and Suarez, 1983). Since a few researchers have argued that for theoretical reasons the coefficient of relative risk aversion should not exceed unity (see Brigs, Dionne and Eeckhoudt, 1989), we have also made calculations with a value of 0.9.

Other crucial parameters are the size of damage from the accident and its probability, which were taken from the U.S. nuclear fuel cycle study. We retained these values, dropped the hardly meaningful probability value of 0.5 and kept the 0.1 and 0.001 value to check for sensitivity.

The estimate of X as a share of income lost due to an accident in the "affected area" leads to serious methodological issues that will be taken up in the last section, as this is but one of several possible modelling strategies.

In this section and in the following one, these considerations are neglected (as in Ch. 17). We arbitrarily assume three values for the associated loss arising from an adverse event: (a) 9% of income, about the damage expected according to CEPN estimates for a region of about 300 Km radius around the reference site of Tricastin, chosen for the original ExternE Nuclear study, (b) for comparability, we also kept the 14% estimate of Chapter 17, which is referred to a much smaller population (53,000 compared to an estimate of 11.7 million of the reference area for the French site), and (c) likewise, we considered the probability of the severe accident with core melt and significant release taken from the CEPN Report (Schneider and Tort, 1996) which amounts to 1.9×10^{-6}.

Valuations referring to this description of the French reference case are found in the last row and columns of Table 1, for both utility functions, together with values already produced in Ch. 17. In all specifications, the ex-ante/ex-post ratio is above unity and the "French" specification is very close to the "American" one, but the valuation of the event is not dramatically altered by allowing society to be risk-averse, the main improvements entailed by Eu over the old, risk-neutral ExternE approach.

Table 1: Results of Chapter 17 Approach (Expected Utility)

p = prob.	rel risk aversion		Ratio ex-ante/ex-post damage					
			Utility function I			Utility function II		
			X=50%	X=14%	X=9%	X=50%	X=14%	X=9%
1.00E-01	2.5		2.118	1.184	1.112	1.779	1.173	1.108
1.00E-03	2.5		2.434	1.209	1.125	1.990	1.197	1.121
6.20E-05	2.5		2.438	1.209	1.126	1.992	1.197	1.121
1.90E-06	2.5		2.438	1.209	1.126	1.992	1.197	1.121
1.00E-01	0.9		1.300	1.062	1.039	1.228	1.059	1.037
1.00E-03	0.9		1.339	1.069	1.043	1.263	1.066	1.042
6.20E-05	0.9		1.339	1.069	1.043	1.263	1.066	1.042
1.90E-06	0.9		1.339	1.069	1.043	1.263	1.066	1.042

C. The Measurement of Ex Ante WTP with Non-Expected Utility Models

The W/D values shown in Table 1 were derived on the basis of Ch.17 - ExternE Methodology (Part II) under the assumption that individual preferences conform with the axioms of Expected Utility theory.

The actual application of this procedure in real decision making processes would be a big step towards a more theoretically grounded and welfare based valuation of social risks. At the same time, the use of the Expected Utility model may be subject to some criticisms. There is, indeed, a recent and ever-growing literature which argues that people's preferences do not conform with the received Eu model. This may occur for different reasons, well documented by individual decision making experiments based on monetary gambles (see Camerer 1996, for a comprehensive survey), which may also be relevant in the context of the assessment of willingness to pay to avoid facing certain social risks. Perhaps, one of the most documented effect is that people tend to overweight small probabilities, which, in the present context, would obviously lead to higher W/D values than otherwise predicted on the basis of the Eu model (as in Table 1). But there are other cognitive processes which may also be relevant, which include the effect of disappointment, regret, aversion to Knightian uncertainty, loss aversion, etc. Several researchers have recently focused on some of the above effects to produce a new set of theories which generalise in one way or another the Eu model.

In the following we will derive W/D measures, following the Ch. 17 ExternE Methodology, but using two such new theories: the first one is the model of Expected Utility with rank dependent probabilities (EURDP henceforth), originally proposed by Quiggin (1982) and Yaari (1987), and then extensively analysed by a number of authors (references in Karni and Schmeidler, 1991); the second one is a model of "disappointment" aversion, considered here in the version developed by Gul (1991).

We now present the two models and derive the implied W/D values; then in the next subsection we will explain why we believe that they may be particularly important in the context of the evaluation of social risks.

Expected Utility with Rank Dependent Probability

In EURDP, the value of a lottery $(z_1, p_1; \ldots; z_n, p_n)$, where (w.l.t.) $z_1 \leq z_2 \leq \ldots \leq z_n$, is given by :

$$V(z_1, p_1; \ldots; z_n, p_n) = f(p_1)v(z_1) + \sum_{i=2}^{n} v(z_i)\left[f\left(\sum_{j=1}^{i} p_j\right) - f\left(\sum_{j=1}^{i-1} p_j\right)\right]$$

where v is a continuous, strictly increasing utility function; and $f:[0,1] \rightarrow [0,1]$ is a continuous, strictly increasing probability transformation function, which transforms probability according to the rank ordering of outcome. (Clearly, when f is the identity function, the model reduces to expected utility).

Various authors have commented on the possible shape of the probability transformation function; and there is now fairly general agreement that f is concave near 0 and convex near 1, taking the characteristic shape shown in Figure 1. From a theoretical viewpoint, this shape is explained by well-known arguments from the literature on cognitive psychology (see, in particular, Kahneman and Tversky, 1979; and Tversky and Wakker, 1995), which suggest that a small change in probability has typically a bigger impact near the limits of the probability range [0,1] - that is, when it changes the state of an event from impossible to possible and from possible to certain - than when the same change occurs in the middle of the interval. Among other things, this implies that low probabilities are typically overweighted and high probabilities are underweighted.

Figure 1: An Over-Weighting Probability Function in EURDP

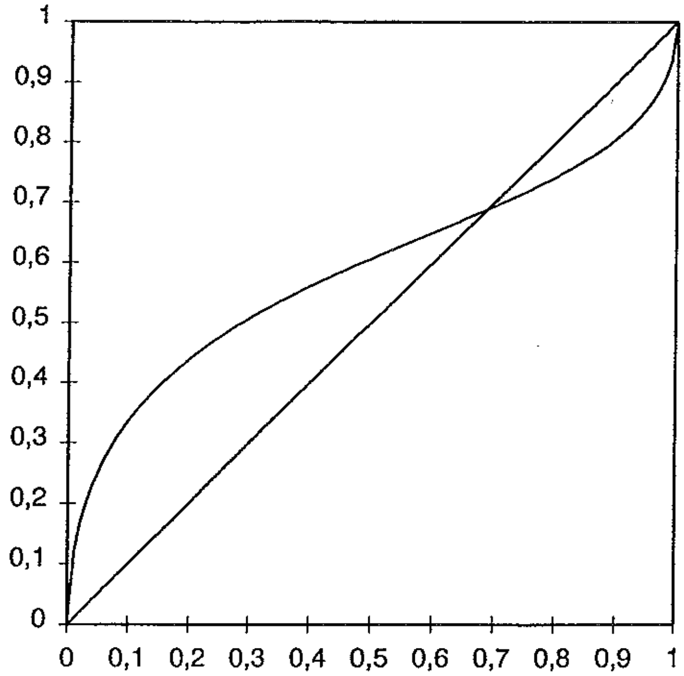

Figure 2: Eu and EURDP for Binary Gambles

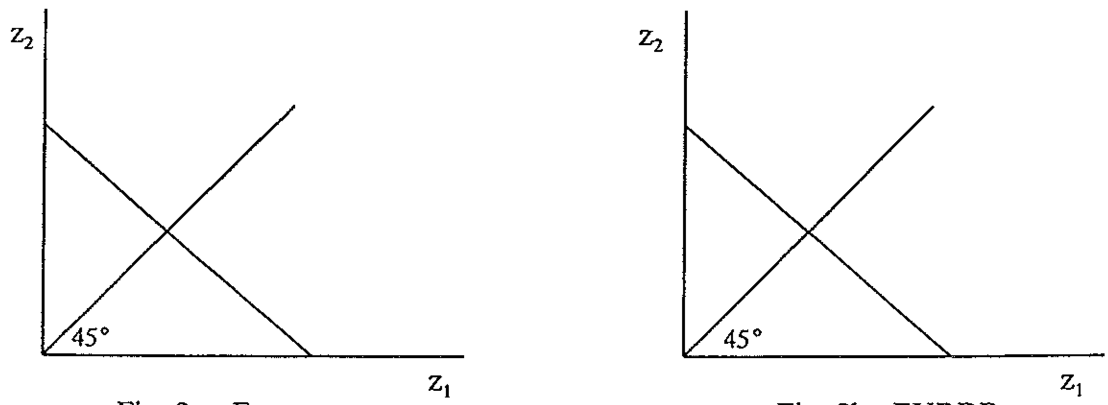

Fig. 2a - Eu   Fig. 2b - EURDP

It should be noted, however, that the qualitative change induced in behaviour by the model is more fundamental than simply the overweighting of probabilities; or, more precisely, the overweighting is an expression of a fundamental qualitative change in behaviour, which the model implies when the individual moves from a situation of certainty to a situation of uncertainty. Such qualitative change can be very well illustrated with reference to binary gambles of the form (z_1,p; z_2,1-p). For such types of gamble the model gives values:

$$V(z_1,p;z_2,1-p)=(1-f(1-p))v(z_1)+f(1-p)v(z_2) \quad \text{for} \quad z_1 \geq z_2$$

and

$$V(z_1,p;z_2,1-p)=f(p)v(z_1)+\left(1-f(p)\right)v(z_2) \quad \text{for } z_2 > z_1$$

Put in words, the values given to the lotteries depend on whether z_2 is greater than z_1 or vice versa. But it is more interesting to note how behaviour is affected near certainty. To see this, consider the graphical representations in Figure 2a and 2b. Both figures display gambles of the form $(z_1,p;z_2,1-p)$ in the (z_1,z_2)-plane. The 45° line is the certainty line where $z_1=z_2$. In Fig. 2a, an indifference curve predicted by Eu is displayed, with slope along the indifference curve given by $-p/(1-p)$[3]. In Fig. 2b, an indifference curve for EURDP is shown, for which the slope from the right (i.e. for gambles with $z_1 \geq z_2$), is $-\frac{(1-f(1-p))}{f(1-p)}$, and that from the left (i.e., for gambles $z_2 > z_1$), is $-\frac{f(p)}{1-f(p)}$. The kink in the indifference curve induced by this latter model is equivalent to an attitude towards risk called by Segal and Spivak (1990) 1st order risk aversion (as opposed to the attitude implied by Eu, called 2nd order risk aversion), which the two authors show to have quite important implications in the analysis of optimal portfolio and optimal insurance decisions. For our purpose here it is sufficient to appreciate the origin of the qualitative change in behaviour, of which the kink is an expression, and which typically occurs when an individual moves from a situation of certainty to one of uncertainty.

Moving now to our specific exercises, we started from the following transformation function which fits the shape shown in Fig. 1:

$$f(q)=1-\frac{(1-q)^{\gamma}}{\left(q^{\gamma}+(1-q)^{\gamma}\right)^{\frac{1}{\gamma}}}$$

Originally suggested by Tversky and Kahneman (1992), such a transformation function has been estimated by Camerer and Ho (1994) on the basis of the results of several experimental studies, yielding an estimated value g= 0,56. Hey and Orme (1994) give a similar estimate.

This transformation function has been used to derive the values of W/D shown in Table 2, where W has been obtained from the expression:

$$V(M-W)=f(p)v(M,A^*)+\left(1-f(p)\right)v(M,0)$$

with the same v(.) function used for constructing Table 1.

As the data reveal, the use of EURDP generates a much more dramatic departure from EED evaluations than the application of the Eu model. It is clear for instance that reduction in the probability of the severe accident is partly offset by its "transformation", so that the "French" scenario event, which has an ex-post expected damage probability of about 1/50th the

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[3] To see this, simply note that according to Eu it is $V(z_1,p;z_2,1-p)=pv(z_1)+(1-p)v(z_2)$. Along an indifference curve utility is constant, so that the slope of a generic indifference curve is $-pv'(z_1)/(1-p)v'(z_2)$. Since along the certainty it is $z_1=z_2$, it immediately follows that along certainty the slope of a generic indifference curve is indeed $-p/(1-p)$.

"American" one for the affected people, will actually be perceived as only about 1/11th. In particular, a cost-benefit analysis of accident probability reducing interventions is much more likely to fail the test.

Disappointment Aversion

The last three columns of Table 2 report the values of W/D calculated on the basis of a model of "disappointment aversion". Crucial in this case are considerations of "what might have been": disappointment specifically arises when an individual receives an outcome from an uncertain event which falls short of some previous expectation. Conversely, if the actual outcome is better than the previous expectation, the individual experiences elation.

Originally proposed by Bell (1985) and Loomes and Sugden (1986) as an explanation for different violations of expected utility theory (including the Allais paradox), a very straightforward model of disappointment aversion has been more recently proposed by Gul (1991). In Gul's model, the value of a generic lottery $\tilde{z} = (z_1, p_1; \ldots; z_n, p_n)$ is given by:

$$V(z_1, p_1; \ldots; z_n, p_n) = \gamma(a)\left[\sum_{v(z_i)>V(\tilde{z})} v(z_i)\frac{p_i}{a}\right] + (1-\gamma(a))\left[\sum_{u(z_i)\leq V(\tilde{z})} v(z_i)\frac{p_i}{1-a}\right]$$

where $a = \sum_{v(z_i)>V(\tilde{z})} p_i$, $\gamma(a)=a/[1+(1-a)]\beta$ and $\beta \in (-1,\infty)$.

Intuitively, the model divides the utility associated with a gamble into two partial expected utilities (with normalised probabilities): an elation part, the first term on the right-hand side of the expression quoted above, and a disappointment part, the second term on the right-hand side. Then, the weights $\gamma(a)$ and $(1-\gamma(a))$ are used to characterise the attitude towards disappointment, with disappointment aversion occurring when $\beta>0$, which implies that disappointing outcomes are overweighted and elation outcomes are underweighted. (Note that $\beta=0$ implies the expected utility model). Camerer and Ho (1994) provide an estimate of b of around 2,5.

On the basis of such estimate we obtained W as solution of:

$$V(M-W) = \frac{1-p}{1+p\beta}v(M,0) + \frac{p(1+\beta)}{1+p\beta}v(M,A^*)$$

from which we have then calculated the values W/D reported in Table 2.

The model predicts WTP values between 5 and 10 times bigger than those based on the EED methodology. Notice, however, that the differences from the analogous values obtained under the Eu model, while quite substantial, are significantly less than those obtained under EURDP, particularly in the case of very low probabilities.

While a choice between EURDP and the disappointment aversion model is not an easy task in the current state of the art, it is worth mentioning experimental evidence by Hey and Orme (1994) who report much better empirical support for the former.

Table 2: Results of Non-EU Approaches (CRRA utility function)

p = prob.	rel risk aversion		Ratio ex-ante/ex-post damage					
			EURDP			DA		
			X=50%	X=14%	X=9%	X=50%	X=14%	X=9%
1.00E-01	2.5		5.480	3.807	3.641	4.818	3.196	3.044
1.00E-03	2.5		82.879	43.009	40.168	8.466	4.217	3.928
6.20E-05	2.5		302.628	151.596	141.248	8.529	4.230	3.939
1.90E-06	2.5		1428.03	709.163	660.383	8.533	4.231	3.940
1.00E-01	0.9		4.084	3.525	3.468	3.449	2.938	2.886
1.00E-03	0.9		47.495	38.235	37.330	4.671	3.732	3.641
6.20E-05	0.9		167.835	134.231	130.960	4.687	3.742	3.650
1.90E-06	0.9		785.602	627.326	611.940	4.688	3.742	3.650

D. Preferences, Rationality and Individual Measures of WTP.

Having in the previous section discussed how individual WTP measures to avoid facing certain social risks may be affected by the overweighting of small probabilities or by considerations of disappointment, one relevant question is what to do then with such measures.

The problem here is similar to the old question of whether or not risk aversion should be a relevant element in the evaluation of social risk. But there is an extra dimension here, arising from the fact that most of the psychological effects generating deviations from Eu are considered by some scholars forms of irrational behaviour (an argument which does not apply to risk aversion). If that position should prevail, then one may well argue that the policy makers should not be guided in their final decisions by *irrational* valuations and should perhaps disregard altogether lay people's WTP.

In order to reply to such criticism, it is useful to start from the observation that the importance which certain cognitive processes might have in influencing lay risk assessment was, indeed, already anticipated by the aforementioned Ch. 17. In that previous analysis, however, the effects of the cognitive processes were only analysed in terms of the difference in the probabilities with which experts as opposed to lay people determined the likelihood of a certain nuclear disaster.
That is certainly an important element which may affect lay people WTP; but is quite different from the issues addressed by the non-Eu literature. To be more specific, the biased assessments of probabilities is a phenomenon which has typically to do with the fact that lay people do not normally have an objective knowledge of probability. Psychologists (like Tversky and Kahneman, 1981) argue that individuals form an assessment of the likelihood of a certain event by considering and retrieving from memory, situations in which the event has

occurred. The problem is that situations in which an exceptional but dramatic event, like indeed a nuclear accident, has occurred are much more "at hand" to memory than cases in which the event has not occurred. The result is that lay people tend to over-estimate the likelihood of such dramatic event, since their assessments are based on "non-representative" events. In the ExternE methodology it was argued that "to the extent that perceptions affect behaviour, perceptions are what matter", because, among other things, although "nuclear power plans or hazardous waste sites have, according to the experts, negligible risks to the public, they can have large effects on property values" (Ch. 17, p. 144).

We believe that the arguments developed in the present paper, and in particular those considered in the previous section, have some extra reasons to be considered in the evaluations of social risks.

It is important to note, first of all, that the problem of overweighting of small probabilities or that of disappointment aversion do not result from misjudgements or misperception of probabilities: the probabilities considered by both models are objectively given as, indeed, they are in most of the experiments which have motivated the developments of the non-Eu literature, like the famous Allais paradox.

Rather, the departures from the predictions of the Eu model result from behaviour which appears strictly related to individual preferences: in the EURDP model, in particular, it is the qualitative change which typically occurs from a situation of certainty to one of uncertainty which generate the over-weighting of small probabilities; in the disappointment model, the deviations from Eu depend on considerations of "what might have been". For example, consider an individual who, when evaluating his WTP to avoid the low risk involved in the siting and operation of a nuclear plant, may take into account not only the risk involved in the operation of the plant, but also the fact that if the plant is built and a disaster does occur, he will suffer an extra loss of utility because of the disappointment he may experience for not having reported a WTP high enough to prevent the building of the plant. There is no misperception in the behaviour of the individual. On the contrary, we would say that his behaviour is only motivated by his preferences or his welfare.

We believe that there is some genuine confusion about the use of the term 'preferences' or utility in economics. On the one side, preferences and, in particular, coherence and consistency of preferences, have been used to identify rationality of choice. Under that interpretation, the Eu axioms have been regarded as the fundamental criteria for coherence in individual decision making under uncertainty (see, e.g. Hammond, 1988). Conversely, behaviour which deviates from such criteria is considered as a form of irrational behaviour. There is, however, another, perhaps even more classical - Benthamite - interpretation of preferences, as simply defined as self-interest. Under this second interpretation, the rationality of choice is seen as nothing else but "the unfailing pursuit of self-interest" (Sen, 1985).

According to this interpretation, we then believe that if a person is actually experiencing a feeling of disappointment when some adverse event occurs or is averse to a situation of risk and uncertainty as such (as implied by EURDP), then it is probably rational for him to take note in advance of such feelings and, in the context of social risks evaluations, state a higher than otherwise expected WTP.

A remarkably different approach to the problem of the normative value of deviations from Eu is represented by prospective reference theory (PRT), as developped by Viscusi and his collaborators in a number of contributions (see Viscusi, 1989; Smith, 1992). This is the only alternative to Eu already considered by Ch. 17.

According to PRT, individuals tend to adjust their valuation of probability by continously updating their beliefs on the grounds of experience, in a Bayesian fashion. Thus, at any given time, their assessment will be a weighted average of their initial (prior) valuation p_0 and of their experience p_1. With weights given by h and k, their (temporary final) assessment of the probability of an event will be given by:

$p = (hp_0+kp_1)/(h+k)$.

Viscusi stresses how the weights depend on the particular risk experience in question and has attempted to estimate the ratio h/k in several risky frameworks, like job decisions of potentially exposed chemical workers (Viscusi and O'Connor, 1984), consumption of dangerous products (Viscusi et al., 1987) and even the overall rating of different risks as provided by the famous psychological studies by Lichtenstein et al. (1978) (Viscusi, 1985). The presence of a Bayesian learning process is widely confirmed, although the pace of learning, and hence the estimates of h and k, are highly variable.

Note that this approach avoids in principle the problem of choosing between "objective" probabilities or weighing them in decision making, but it states that "subjective" probabilities are adjusted by individuals themselves, usually towards the values singled out by technical experts.

To be operational, the last part of Ch. 17 interpreted p_0 as the lay people estimate of probability, p_1 as the expert assessment and k as the weight given by lay people to the expert. Hence they proceeded to calculate WTP by means of the usual Eu model, with various values of h and k. However, unlike in Viscusi's studies, the chosen values seem rather arbitrary. The only meaningful interpretation of this exercise consists of taking the lay assessment as a contingent outcome of the Bayesian learning process, while giving to the expert a zero weight. This leads of course to results where the ex-ante/ex-post ratio closely resembles the p_0/p_1 ratio, as in the last row of Table 17.3 in Ch. 17. This approach might have been replicated if estimates of the lay people probability assessment had been available for the reference social context[4].

However, this is only a static picture which does not fully acknowledge the nature of the process described by the PRT approach. In other words, it does not take adequately into account how public perception of nuclear risk may change over the years and between locations.

Indeed, the appeal of PRT for the nuclear as well as for other risky decisions lies in its dynamic character. If people learn from experience, this may well be an explanation of why they seem to feel more comfortable with nuclear power where this has been safely run for a

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[4] The study currently being carried out by CIEMAT in Spain could be used after completion.

long time, under constant technological and managerial conditions (as in the French case), while confidence is lower where nuclear is not well known or has been run by several utilities with different technological specifications.

Thus, PRT could well represent the analytical framework for the analysis of public perception of nuclear power, which may be eventually turned into social cost estimation. Unfortunately, no such study is currently available and this precludes at present its use for valuations.

E. Some Notes on Progress Towards a More Adequate Modelling Strategy for Severe Accidents (And Other Severe but Uncertain Impacts).

Who Should a Preference Functional be Applied to?

It is well known from the work of the ExternE project that impacts of pollutants dispersed through the atmosphere or other environmental media are such that a remarkable share of the impact occurs at a long distance from its source. Cutting the impacts by assuming them to be limited to certain neighbouring region is not only arbitrary, but it entails remarkable differences in the valuation of the share X, which is generally higher the smaller the affected area, since higher concentration of pollutants are found close to the plant.

With a risk-neutral social cost function like (1), which is linear both in economic damage of the accident and in its probability, it is feasible to evaluate all damages first and multiply them eventually by the probability of the adverse event, which is of course the same for everybody. This is not the case with any nonlinear function like (2) and *a fortiori* with functions which are not even linear in probabilities. Indeed, if individuals' utility functions are risk-averse, and if they are exposed to different damage values, evaluating the function for a mean damage leads to underestimation of total ex-ante WTP [5]. This effect is larger if any non-Eu functional (nonlinear in probabilities) is used.

As a consequence, a first alternative modelling strategy to the one employed in Ch. 17 would require that damage is estimated for each representative individual, and WTP evaluated accordingly. Total ex-ante social costs should be evaluated by summing individual WTP's after the selected functional has been employed.

In practice, the representative individual may consist of the average inhabitant of each cell of the grid for the local and regional range impact dispersion models already employed within the ExternE framework. Inclusion of the chosen functional(s) for social cost valuation under

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[5] For example, assume function I of section B holds, i.e. people are Eu maximisers with a relative risk aversion parameter of 2.5 and a "French" accident probability of 1.9×10^{-6}. If there were for simplicity only two affected communities of the same size, with respective damage of 50% and 10% of their common income, the former would have an ex-ante WTP 2.438 times larger than ex-post damage, while the latter would multiply ex-post damage by 1.141 only; hence the average ex-post damage would be 1.789 larger than ex-post damage. However, if we directly apply function I to the mean damage of the accident (30%), the ratio would be only 1.572.

risk within computer programs like ECOSENSE or PATHWAYS should be a relatively easy task. The approach might also perhaps be embodied in the COSYMA Code used for the CEPN evaluation of accidents.

Inclusion of any valuation approach into one of the mentioned external cost estimation tools is beyond the scope of the current project. However, in order to appreciate how a proper application of preference functionals may affect the estimate, we developed a simulation exercise with the following symplified assumptions[6]:

- each local community evaluates the event by means of a utility function of type I as described in section B, with a constant relative risk aversion coefficient of 0.9
- the risk to which each community is subject depends only on its location with respect to the power station
- the Tricastin site and three areas of less than 100 Km radius around them with actual population data are used for assessment of the local impacts
- a larger area of radius between 100 and 500 Km is considered, with a similar population density (74.5 inhab./squared Km)
- all impacts decrease exponentially with distance from the site, so that impacts 10 Km from the site are five times as large as 100 Km away; this is consistent with typical dispersion patterns from an accident and with proportional dose-response functions such as those used for radiological health impact in the CEPN study. However no account is taken of the actual wind direction; that is, all directions have the same probability
- total assessment for the local range equals estimates of CEPN, increased by 30% in order to include indirect costs
- the population income is given by the French per capita average for 1990, so that it is comparable with monetary valuations used within ExternE.
- all damage occurs within one year. Note that this is the same assumption taken in Chapter 17, but it is questionable as a large part of the damage is deferred by years. However, results of the ExternE Nuclear study do not allow for an easy split of damage across time.

Results obtained in this exercise are shown in Table 3. The Table shows that fear of the event, and therefore willingness to pay to avoid taking such risk, may change with distance from the site. It seems to give a fairly realistic picture of how the risk of a severe nuclear accident is perceived, notably close to the plant. On the other hand, the ex-ante/ex- post ratio far from the plant (where accident damage is a limited share of wealth) converges towards the ratio between transformed and original (expert) probability.

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[6] Although some real data have been used, others are quite arbitrary so that results are by no means a preliminary evaluation.

Table 3: Results of Three Approaches by Source Term and Distance from the Accident Site

	Damage/ income %		Eu		EURDP		DA	
Distance Km	ST2	ST21	ST2	ST21	ST2	ST21	ST2	ST21
15	100.0	14.8	10.000	1.079	5838.2	629.9	34.99	3.757
100	28.3	4.1	1.156	1.019	678.1	597.9	4.054	3.567
300	1.6	0.2	1.007	1.001	591.0	587.3	3.525	3.503
500	0.1	< 0.1	1.001	1.000	587.1	586.8	3.502	3.500
Mean 0-100			1.305	1.032	765.6	605.5	4.568	3.612
Pop. weighted mean 0-100	46.6	6.8	1.575	1.032	923.3	605.7	5.514	3.613
Mean 0-500			1.015	1.002	627.3	588.1	3.554	3.507
Pop. weighted mean 0-500	3.4	0.5	1.030	1.002	604.4	588.1	3.605	3.508

The Problem of Delayed Resolution of Uncertainty if the Adverse Event Occurs

A second and more fundamental modelling problem arises from careful analysis of the situation of people who might be hit by a severe nuclear accident. In fact, if the accident did occur, part of the costs could then be regarded as certain for some exposed individuals (though not the same for all of them). As explained in the CEPN Report (Schneider and Tort, 1996), some would face early deaths and diseases, others would have to be relocated, and a larger population would incur output losses.

However, a significant part of the damage would in turn represent a (second stage) risky situation. In particular, several people would have increased mortality or morbidity chances, but even if the assessment is regarded as certain in the aggregate[7], it is still uncertain who will be affected.

In other words, the approach we have outlined above to the valuation of social risk, whether based on Eu or on its generalisations, rests on a further oversimplifying assumption: that if the adverse event A* occurs, the individual knows in advance and for certain which consequences such occurrence means for him, so that the uncertainty reduces to a very simple binary lottery: the adverse event occurs, the adverse event does not occur.

That, however, is certainly not the case. On the contrary, the most uncertain aspect of certain environmental risks, like those involved in the setting up of a nuclear plant, arises from the fact that not even experts can say precisely which effects the accident will cause and, especially, when such effects will occur and who will be affected.

[7] Recall that overall uncertainty concerning results is being analysed within sub-task 1.4 of the ExternE Maintenance and Extension project.

Typically, for example, a nuclear accident can cause various different effects, which, in addition, will occur at different times: a certain number of persons will instantaneously die because of the accident; a certain number will shortly get leukaemia, and of these some people will die after some time; others still will get ill only after some time, which may be months or years; others will be hit by radionuclides but not lose any years of life, etc..

All this results in a much more complicated lottery than the binary lottery considered up to now. Delayed resolution of uncertainty regarding certain effects, for example, knowing whether a person will or will not get leukaemia, may in particular have important effects on the welfare of people.

Eu deals in a very simple way with the issue, it disregards the problem altogether. This comes from a well known assumption regarding multi-stage lottery called "the reduction of compound lottery axiom" (RCLA).

To illustrate with the simple example of the uncertainty of getting or not getting leukaemia, which we treat now as the definite adverse event A*, the situation can be represented as shown in Fig. 3a . There is a probability q that an accident occurs in the nuclear plant and a probability 1-q that nothing occurs. If the accident occurs, there is a probability r of a person getting leukaemia after sometime and a probability 1-r of remaining healthy. In other words, there is a two-stage lottery, with the first stage being the accident occurs/doesn't occur and the second being falling ill/not falling ill.

According to RCLA (and to Eu) the fact that uncertainty resolves into two-stages doesn't matter in the evaluation of the lottery: writing p=qr, we are indeed back to the binary lottery (A*, p; 0, 1-p), which we have considered up to now (see Fig. 3b).

One may argue, however, that there is a fundamental difference between a person knowing now whether s/he will get leukaemia or not, and the situation of living with the uncertainty of becoming ill. An alternative procedure to evaluate the lottery is known as the certainty equivalent mechanism (CEM). The procedure simply entails evaluating a multistage lottery by recursively substituting the lotteries down in the decision tree with the relative certainty equivalent[8]. Thus, for example, let CE(r,A*) be the certainty equivalent that a person attaches to the simple lottery (A*, r; 0, 1-r). Then the two-stage lottery is reduced to (CE(r,A*), q; 0,1-q) (see Fig. 3c).

It is important to stress that under Eu, the value given to (CE(r,A*), q; 0,1-q) is always equal to the value given to (A*,qr; 0,1-qr), so that the value given to the two-stage lotteries does not change according to which reduction procedure, whether RCLA or CEM, is applied[9]. However, under different generalisations of Eu, that is no longer true.

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[8] The certainty equivalent of a lottery is defined as the certain consequence that if received by a person instead of the lottery will let him on the same utility of the lottery ??.

[9] To see this, note that if CEM applies with Eu, $CE(r,A^*)=u^{-1}[ru(A^*)+(1-r)u(0)]$. Then, $V(CE(r,A^*), q ; 0, 1-q)=qu(u^{-1}[ru(A^*)+(1-r)u(0)])+(1-q)u(0)$, which is of course equal to $V(A^*,qr ;0,1-qr)=qru(A^*)+(1-qr)u(0)$.

In particular, according to EURDP, we have

$$f(qr)V(M,A^*)+(1-f(qr))V(M,0) \quad (3)$$

if RCLA applies, and

$$f(q)f(r)V(M,A^*)+(1-f(q)f(r))V(M,0) \quad (4)$$

if CEM applies[10]

The two expressions may be useful in studying the effect that delayed resolution of uncertainty may have on people's attitude towards social risk. In particular, if one sees the evaluation obtained under the RCLA as the evaluation which should apply in case of no interval of time between the occurrence of the accident to the nuclear plant and the knowledge of its effects (in the example the event of getting leukaemia), then a positive (negative) difference to the second expression could indicate an aversion (preference) for a delayed resolution of uncertainty.

In that respect, it is perhaps useful to note that Segal (1987) offers two main theorems which provide general conditions to determine the direction of preferences between the two expressions, and hence the attitude towards immediate or delayed resolution of uncertainty, according to the shape of the decision weighting function f(.). An interesting characteristic is that the conditions which imply preference for earlier resolution are remarkably similar to those entailed by the S-shape shown in Fig. 1, which (we should add) also guarantee risk aversion (aversion meaning preserving spread) for the single-stage lotteries. This accords with intuition; though clearly, specific experimental tests or questionnaire evidence may be appropriate for the issue.

This kind of uncertainty is not however peculiar to the nuclear fuel cycle, but we think it should be stressed as a contribution of this sub-task to the analysis of all fuel-cycles which are often concerned with similar risky situations. Recall that in general, the value of a statistical life (or nonfatal disease) is estimated within a certain risky situation, either actual (where it is taken from labour market or from defensive expenditure studies) or hypothetical (if it is derived from CV usually with reference to a particular risky gamble). If such valuations are the outcome of information processing as described by a preference functional $V(\mathbf{p},\mathbf{X})$ - where $\mathbf{X}$ is a vector of consequences and $\mathbf{p}$ are their probabilities, they should in principle be corrected in order to be applied to a different risky situation $(\mathbf{q},\mathbf{Z})$. Unfortunately, we could not find this kind of transformation effectively performed so far in the economics literature. While this modelling strategy seems more appealing in principle, its application is probably beyond the current state of the art as may be introduced into the ExternE accounting framework.

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[10] If CEM applies with EURDP, $CE(r,A^*)=u^{-1}[f(r)u(A^*)+(1-f(r))u(0)]$. Then, $V(CE(r,A^*), q ; 0, 1-q)=f(q)u(u^{-1}[f(r)u(A^*)+(1-f(r))u(0)])+(1-f(q))u(0)=f(r)f(q)u(A^*)+(1-f(r)f(q))u(0)$, which is different from $V(A^*,qr ;0,1-qr)=f(qr)u(A^*)+(1-f(qr))u(0)$.

Meanwhile, it must be noted that direct use of the VOSL (and its morbidity and materials damage counterparts) irrespective of the general risky situation, as done at present within ExternE as well as within other social cost valuation exercises, amounts to rejecting the RCLA: in fact the second stage lottery (in the example, whether or not a person will get a disease after the accident) is replaced by its certainty equivalent, given by the selected VOSL. In this paper we accepted this approach and apply valuation functionals under uncertainty only to the first stage lottery (whether or not the accident occurs). Nonetheless, this approach may be criticised as inconsistent with RCLA (as much evidence indeed is) and may be generally flawed.

This fact ought to be stressed as application of correction for decision making under risk to only a few energy production cycles may not represent fair treatment of these (Meaning?). It is, however, unlikely that the lack of such corrections should be biased against such energy sources as nuclear or hydro, which are characterised by inherently more risky adverse effects.

Figure 3: The Problem of Delayed Resolution of Uncertainty

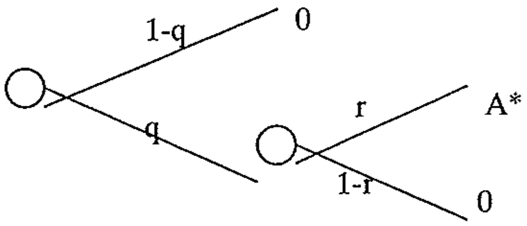

Fig. 3a - A two-stage lottery

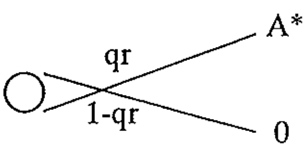

Fig. 3b - The RCLA

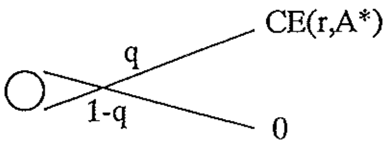

Fig. 3c - The CEM

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Summary and Conclusions

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A. Introduction

In the assessment of the nuclear fuel cycle one of the most contentious issues has been the valuation of serious nuclear accidents. The consequences of such accidents are very large and widespread. In monetary terms these could amount to billions of ECU, and there is a high level of public concern (admittedly one which varies from country to country) about the possibility of such an accident. At the same time, the expert opinion is that the type of reactors used in Western Europe have a very low probability of the kind of failure that would produce a severe accident. The exact values associated with an event in which there is a failure of containment and hence significant potential damage vary form one set of experts to another but in general we are looking at probabilities in the order of 10^{-6} and lower. Thus estimated probabilities of this order result in expected damages of thousands of ECU per accident. For many policy-makers, this does not reflect society's willingness to pay to avoid a nuclear accident.

The ExternE Methodology report noted the difficulty of using the expected value of damages in the case of severe nuclear accidents and prepared an addendum to the main report indicating how, in the view of the economists on the team, such issues should be addressed. There were three key questions that needed to be answered.

The first was the need to establish an agreed set of consequences of a nuclear accident and attach probabilities to these consequences. As the paper by Tort shows, there remain wide divergence between national teams on what consequences should be looked at and hence what probabilities should be attached to those consequences. This implies that we cannot take 'expert' opinion as single-valued and objective, and policy-makers have to choose between different sets of consequences and probabilities.

Related to that is the issue of how one treats public estimates of probabilities versus expert estimates in the assessment of accidents. Clearly both matter; one cannot ignore the careful analysis carried out by the experts, but at the same time one cannot overlook the opinions of the public, whose willingness to pay we are interested in. In the case of accidents which occur with reasonable frequency, this problem is resolved by looking at the relative frequencies of different accidents and basing the probabilities of such accidents on the relative frequencies. For nuclear accidents, there is no such history to draw on. There have been hardly any major incidents with serious consequences in the history of nuclear power; the one at Chernobyl is not considered relevant to the reactors deployed in Western Europe. Hence the divide between public and expert opinion has not narrowed appreciably over time.

The final issue is that account needs to be taken of the public aversion to the risk of accidents. The expected value of damages is not enough. The public is willing to pay something for the reduction in risk *per se,* which is not captured in the expected value.

All these points were raised in the ExternE Methodology report (Chapter 17), reflecting a common opinion of the issues with the US team. A joint paper was published reflecting this opinion (Krupnick, Markandya and Nickell, 1993, henceforth KMN). Using simple examples of accident scenarios, the paper looked at how the costs of accidents would change once allowance was made for the 'disjuncture' between expert and public (or 'lay') probabilities and for risk aversion. The expected utility approach was taken, to provide a thorough theoretical foundation to the analysis. The main conclusions from that paper were:

I. Insofar as one could estimate lay probabilities of nuclear accidents, these were much higher than the expert probabilities, perhaps by as much as two orders of magnitude. Hence accident costs based on such probabilities would be 100 times or more greater than those based on expert probabilities.

II. Allowing for risk aversion had a less clear impact. For typical values of accidents and typical levels of household incomes, the risk premium was fairly small. The result is dependent, however, on the precise form in which risk aversion is quantified and how big the expected loss is relative to current income. With some plausible forms **and** with expected losses amounting to around 50% of income the 'risk-aversion-corrected' estimated damages could be as much as 50 times as high as the expected damages.

This report has taken the above analysis as its point of departure and has developed the discussion of severe accidents further. It looks at all the different aspects of the problem.

The first is the characterisation of expert probabilities. The paper by Tort examines the different source terms and the associated accident probabilities for France, Germany and the UK. The paper by CIEMAT looks, empirically, at how these probabilities vary according to the type of expert consulted.

The second is the estimation of such costs. The paper by Schneider looks at how costs should be estimated and what problems arise in the application of the different methods.

The third is the evaluation of other approaches to estimating nuclear accident costs. Various authors have made attempts to adjust the expected damage approach to allow for risk aversion but, as the paper by Gressman shows, they are *ad hoc* and without proper empirical and theoretical foundations.

The fourth is the elaboration of the risk-aversion analysis of KMN, taking a more realistic example of a nuclear accident and evaluating a more complex set of associated consequences. This has been done in the paper by Eeckhoudt, Schieber and Schneider, which is important in bringing the risk aversion analysis to a level at which it could be incorporated in an external cost estimate.

The final set of issues is the examination of various alternatives to the expected utility approach and ways in which the issue of expert versus lay probabilities can be analysed more formally and in an integrated manner with the analysis of risk. The paper by Ascari and Brenasconi addresses these issues.

In this summary we go over the main findings from these papers, and draw out the lessons for the valuation of nuclear accidents within an ExternE type framework. To some extent we have made progress so that further quantification is possible. But in some other ways we have opened up the debate, which can only be resolved with further research.

B. Expert Probabilities and Lay Probabilities

The paper by Tort reports on the different source terms used in France, Germany and the UK for the analysis of nuclear accidents from a PWR reactor. The key point to emerge from this comparison is the significant differences **in the release categories analysed and in the probabilities attached to those releases.** The comparison is made most clear by looking at the highest release category in each case. For simplicity only figures for release of caesium are given, as indicative of the more volatile compounds, although there are differences in the relative releases of other compounds in the different source terms. The figures are as follows:

Table 1: Release Scenarios for Different Countries

Country	Maximum release of Cs (%)	Probability of occurrence	Comment
France	10%	$2\text{-}3.10^{-6}$	Assumed to occur in single release phase without energy. Only 4 release scenarios considered. Next category of accident has only 1% release
Germany	70%	10^{-7}	Six release scenarios included. Next category has 37% release of Cs
UK	50%	$2.4.10^{-9}$	12 release scenarios considered. Next category of accident has only 40% release of Cs.

Source: See paper by Tort in this report.

This makes cross country comparisons extremely difficult. But, even more importantly, it makes it difficult to accept that there is a unique expert view of the accident probabilities that can be defined as objective. If the public is presented with such a table it would say, with justification, that the accident scenarios and their associated probabilities are determined partly by judgement and partly by more 'objective' considerations. Hence, it could be argued, a public view of such accident probabilities should also be given some consideration. We return to this point later.

Differences in the professional judgements about nuclear safety are also highlighted in the paper by CIEMAT. Following the approach of Mitchell (1980) and Lindell and Earle (1983), they interview different groups of experts in Spain to determine their view on this question. The conclusions are similar to those of the earlier studies. Experts with a greater knowledge of the nuclear sector regard it as a safer source of energy than experts involved in renewable energy development or those dealing with environmental and conventional energy sources. Familiarity diminishes the risk, even for technicians. Unfortunately the conclusions are only qualitative; we do not know how these differences in perception translate into differences in accident probabilities. That would be a useful direction of further research.

C. Alternative Approaches to Valuing Risk in Nuclear Accidents

Gressman has reviewed in some detail other approaches to including risk aversion in the assessment of nuclear accidents. The main alternatives are the following:

i. The Ferguson Approach
ii. The Rocard Smets Approach (RS)
iii. The Infras/Prognos Study

All of these suffer from not being based on sound empirical and theoretical data. The Ferguson assumes that the valuation of the risk increases with the square of the number of people affected in the event of an accident. So an accident with a million people impacted has damages one million times that of an accident with only a thousand people impacted. Furthermore, he states that the cost of an accident increases 'exponentially when global equilibrium is threatened'. There is a claim that these assumptions have been tested empirically but no study has been discovered that reports any such tests. The notion that people have a willingness to pay to avoid accidents with a large number of deaths, or other impacts, that increases more than proportionally with the number of deaths in such an impact is sensible and accords with casual empiricism. But to quantify it in terms of a quadratic function is not valid, unless there is evidence to support such a function. It could equally well be any other power function.

The RS approach is to increase the value of an accident by a 'disaster aversion function'. This function multiplies the expected social cost of a nuclear accident by 300 to account for this aversion. The factor of 300 has been derived from some empirical work, but this work is neither cited nor evaluated. RS acknowledge that the factor could be as much as 1000. It is stated that these parameters are derived from a comparison of decisions taken by policy-makers. The problem with such an approach is that it assumes rationality on the part of the policy-makers. If we are trying to determine how to make such decisions **more** rational, it seems tautological to assume rationality in the first place.

RS do not assume that the factor of 300 is constant, but that it holds in the case where the number of deaths is about 1000. For more deaths they state that the aversion factor is proportional to the number of deaths to the power of 2/3. Again this is based on public policy and is subject to the same criticisms as the above[1].

The Infras/Prognos approach is to take the standard deviation of a set of accident probabilities as the measure of the willingness to pay to avoid such an accident. As Gressman notes, the use of standard deviation to measure the risk is common in portfolio theory, in which the mean **and** variance (or standard deviation) determine the ranking of a portfolio. The underlying model is that of maximising expected utility, in the case where the utility function

[1] Thus the use of Rocard-Smets by Pearce (1995) is incorrect. He assumes a factor of 300 for all accidents. Furthermore Rocard-Smets do account for property and other costs and no further addition should be made on that account. Again Pearce incorrectly makes such an addition.

is a quadratic one. Unfortunately it is well established that a quadratic utility is not the appropriate one for decision-making under risk. It exhibits sharply decreasing relative risk aversion, which is contrary to the empirical evidence and it is unbounded, which also creates problems when it is applied for changes in income or wealth outside a narrow range.

In fact the actual use of the mean variance analysis by Prognos/Infras is even more bizarre. They ignore the mean and apply only the standard deviation as a measure of willingness to pay. As Gressman notes this is not valid, either empirically or theoretically.

These different approaches come up with a very wide range of costs for nuclear accidents. Using the Ferguson approach Pearce estimates externality adders of 0.25-0.625 mECU/kWh. These are about 300 times higher than the 'average' expected value estimates of the cost of a nuclear accident. As Gressman notes, however, it is not possible to replicate Pearce's estimates from the data provided by him. Using the Rocard-Smets approach, Pearce obtains an adder of 3.38 mECU/kWh, which is 2,300 times the expected value estimate. As there are errors in his interpretation of Rocard-Smets, it is not possible to interpret this number as a correct application of the latter. The Infras/Prognos study estimates costs with the risk aversion parameter as between 11.4 and 189.6 mECU/kWh, which is between 22 and 367 times the middle of the range of expected values in their study.

In conclusion we would say that such *ad hoc* approaches are to be avoided in a serious analysis of severe nuclear accidents.

D. Formal Representation of Nuclear Accident Risks Using the Expected Utility Approach

The expected utility approach has the advantage that it is based on proper theoretical foundations and can also draw on a range of empirical work. The earlier KMN paper using this approach is taken further by Eeckhoudt, Schieber and Schneider (ESS). They use the constant relative risk aversion function, also used by KMN, namely:

$$U(W) = \{(1-\beta)/\beta\}.W^{\beta}, \text{ with } \beta < 1$$

and

$$U(W) = \ln(W), \text{ with } \beta = 0$$

W is the household wealth. The risk premium is estimated by calculating the certainty equivalent and a comprehensive numerical application is presented for a nuclear accident affecting a country with a population of 56 million inhabitants. Impacts are divided into two areas: local (less than 100 km from the plant and with 2 million inhabitants), and regional (more than 100 km, with 54 million inhabitants). The consequences of an accident are looked at in terms of food ban costs, individual evacuation and relocation costs, and health and loss of life costs. Probabilities for different consequences are estimated as per the French Scenario ST21, which corresponds to a release of about one percent of the core (this is the next scenario down in seriousness from the one presented in Table 1). The coefficient for β is taken at 2.0, from a review of various studies of risk aversion. This is also similar to the KMN study. The authors note that there are some empirical studies that indicate much higher values of β, which would imply much greater risk aversion. There are, however, questions as to how valid these studies are as guides to the values of β and it seems reasonable to take a value of around 2, although some sensitivity analysis would be useful.

The other key assumption is the initial level of wealth of the individual affected by the accident. The authors take a figure of 2.67 million ECU. This is made up of the 'value of life' of 2.6 million ECU and average financial wealth of 0.07 million ECU. The inclusion of the value of life is necessary because the accident can result in a loss equal to 2.6 million ECU; hence one has to assume that the individual has that amount to lose. However there are questions as to what is the correct value of a statistical life and there will be significant variations in financial wealth. As Ascari and Bernasconi point out in their paper, it will be incorrect to replace actual values of these variables with the means when the valuation procedure is non-linear. Hence, in any follow-up work one should look at how the overall costs are affected by replacing the averages by a distribution of values for these and other key variables measuring the costs of the accident.

The results show that, for this particular scenario, the risk adjusted costs are about 20 times the unadjusted costs. This results in an external cost of a nuclear accident of 0.087 mECU/kWh, compared to an unadjusted cost of 0.0044 mECU/kWh, which is considerably less than one obtains from the *ad hoc* methods discussed above, but a number in which one may have greater confidence.

E. Further Developments

The final paper by Ascari and Bernasconi (AB) also takes the expected utility approach but explores some recent development in risk theory as well. Within the conventional expected utility framework they look at the function used by ESS and described above (with constant relative risk aversion β), as well as the following increasing relative risk aversion function:

$$U = -\exp(-bW)$$

This function was also looked at by KMN. The coefficients for the parameters β and b are similar to those taken by KMN. For β they take a mid value of 2.5, against the 2.0 taken by ESS, but also look at a lower value of 0.9. For b the value is selected so that the corresponding coefficient of relative risk aversion (b.W) is equal to the desired value for the mean level of wealth.

The analysis of the risk is taken from the KMN study. The adjustment for risk ranges from 1.12 to 2.44 for a risk coefficient of 2.5 and from 1.04 to 1.34 for a coefficient of 0.9. This is similar to the range obtained by KMN for similar risk coefficients but is lower than the figure obtained by ESS in the above analysis. One reason for the higher adjustment by ESS is that they are looking at much smaller probabilities; we know from the earlier work that the smaller the risk of an accident, the greater the divergence between the expected value and the risk adjusted value. A second reason could be that ESS look at more complex risk scenarios, where there is more than one state of the world in the event of an accident. Given the more realistic nature of the ESS scenarios and the lower probabilities they consider, it seems reasonable to conclude that these two pieces of analysis are not inconsistent, but that the ESS figures are a better guide to policy.

AB then go on to look at some further development in risk theory and how they relate to nuclear risks. The first is the model called the Expected Utility with Rank Dependent Probability (EURDP). In this model the probabilities attached to the different outcomes are adjusted according to a **probability transformation function**. The effect of this adjustment is to give greater weight to events with lower probabilities and lesser weights to events with higher probabilities. This captures the observed phenomenon that people overvalue small probabilities of accidents. It may also capture the fact that lay probabilities of nuclear accidents (which are very small) are cited as higher than expert probabilities. Algebraic forms of the probability transformation function are taken from the risk literature and used to recalculate the ratio of the risk adjusted costs of an accident against the risk unadjusted costs (for the same utility functions as above). The risk adjustment now increases dramatically. For a risk in the range of 10^{-5} it goes up to 141-302 times the unadjusted figure and for a risk in the range of 10^{-6} it goes up to 660-1430 times the unadjusted figure. It is clear that this method gives very large weights to very small probabilities. In the nuclear case it would be interesting to check reported lay probabilities against the adjusted probabilities as given in the adjustment function used by AB.

A second method of modifying the expected utility framework is referred to as the 'disappointment aversion' method (DA). The rationale for this method is that an individual divides his utility from a set of outcomes into two parts: an 'elation' part, where the outcome is better than expected, and a disappointment part, where it is worse than expected. The weights given to the parts depend on the degree of disappointment aversion; the more averse a person is, the greater is the weight, and the more the person will be inclined to select options that avoid such outcomes. As with the EURDP, there is greater willingness to pay to avoid a nuclear risk scenario, where an accident would have a high level of disappointment associated with it. As with EURDP, the disappointment aversion function has been characterised in algebraic form, with quantitative values of the parameters taken from the risk literature. Applied to the nuclear scenarios discussed above, they result in risk adjustments of between 4 and 8.5, much smaller than those obtained with the EURDP. On reason for this is that in the DA method the adjustment varies very little with the probability of the bad event whereas in the EURDP method the probability is the crucial factor.

The debate between these different methods is not resolved in the literature although, as AB note, the opinion seems to be that EURDP is the better method. For the nuclear issue, we would agree with that view. The interpretation of the problem as one of disappointment in the event of an accident seems laboured and the method is not quite as sensitive to either the extent of the loss (as a percentage of income) or the probability of the bad event as one would expect from casual experience and from the application of the conventional expected utility model. Hence, at this stage we would favour the EURDP model.

Given this choice, the question arises as to whether such corrections are justified for the evaluation of nuclear risks? To answer this we have to go back to the key problem identified by KMN -- the 'disjuncture' between lay and expert probabilities of nuclear accidents. The lay public do not believe the expert assessments, but at the same time the experts themselves do not have a unique position on these probabilities. The EURDP model seems to pick up the deviation between public and expert probabilities but does not help with the lack of consensus among experts. However, the EURDP model assumes a constant functional relationship between the expert and lay opinions. To some extent these have been changing, although we do not have a careful documentation of how they have changed. In some countries there has been a degree of convergence, in other the disjuncture remains.

What is needed is: (a) a calibration of the probability transformation function so that for the low probabilities the adjustment reflects public perceptions of such accidents, and (b) a procedure for adjusting this function in the light of changes in public perceptions.

As far as (b) is concerned, AB cite the Bayesian procedure proposed by Viscusi, of adjusting public risk evaluations in the light of experience (Prospective Reference Theory). The formula for the final probability is simple enough and one could adjust the probability function sequentially to reflect such changes, but the difficulty is how to incorporate the 'experience' component. One way would be to conduct periodic surveys of opinion and use that to revise the prior probabilities. However, no such work has been done to date.

AB then go on to raise two further concerns about the valuation of risks in nuclear accidents. One is the issue of using average values of income and impact for the estimation of risk adjusted damages. With non-linear risk functions there will be errors in using averages. No one knows how large the likely errors are, but this is something that needs to be investigated systematically.

The second is the assumption that one can reduce compound probabilities in which there is a sequence of events to a single probability. For example, if an accident occurs, a person may die immediately. If he or she does not die they may get leukaemia after some time and then die, or they may be ill for some time and recover. The expected utility method calculates a single probability of each such event (immediate death, death after X years, illness, no illness), from the conditional probabilities of each of the events. This assumption (called the reduction of compound lottery axiom) may not be valid. With EURDP, for example, the conditional probabilities each have to have the probability transformation applied. This also will impact on the final estimate of willingness to pay, but we do not have an estimate of how big the impact will be.

F. Final Remarks

This report has taken the valuation of nuclear accidents further in a number of respects. First it has demonstrated how *ad hoc* rules are not the way forward, and that the existing estimates based on those rules cannot be viewed as valid. Second it has shown that the expected utility framework can be applied to estimating risk-adjusted nuclear accident costs, and that the numbers are consistent and reasonable. These can offer an immediate correction to the unadjusted costs. Third it has shown that we can incorporate the differences between public and expert assessment of probabilities into a coherent theoretically sound framework. The EURDP model offers a method for doing that, although the precise way in which objective probabilities should be transformed for the nuclear case needs some work.

The report also points to some areas where further work is needed. First, we need to address the differences in 'objective' probabilities that we observe. In the presence of these it is difficult to know how to encompass the range of views from the experts and link them to the lay probabilities. Second we need to establish a link between measured public probabilities and the expert probabilities, thus identifying the probability transformation function. Third, this function should be dynamic, so that changes in public perceptions are incorporated into a new function, according to the adjustment rule suggested by Viscusi. Fourth, the issue of non-linearity has to be addressed. With risk aversion it is not enough to use average values. We need to look at the distribution of incomes and impacts. Finally, where probabilities are being modified the principle of reducing complex events into simple ones is no longer valid. The time sequence has to be modelled, with the appropriate conditional probabilities.

References

For references to papers referred to in the review of individual papers in this volume, but not properly cited, please see the bibliography provided with those papers.

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