14. SUMMARY OF RESULTS

14.1 Definition of Assessment

The ExternE methodology for the evaluation of the external costs of the nuclear fuel cycle has been applied to the total fuel cycle as it exists today in France. The fuel cycle was broken down into 8 stages. In addition, the transportation of material between the sites has been considered. The facilities were assessed for routine normal operation, except in the cases of electricity generation and transportation, where accidental situations were also considered. The impacts of construction and decommissioning of a facility have been included for the electricity generation stage.

The impact pathway approach requires an inventory of the all releases and assessment of all potential impacts, however, within the context of the ExternE project it has not been possible to consider the complete range of possibilities. Therefore, only the most important impacts, called priority impacts, have been included. The highest priority was given to the releases of radioactive material to the environment which could potentially impact public health. Occupational health impacts, from both radiological and non-radiological causes, were also considered to be a priority, even though the extent to which occupational health impacts can be considered externalities has not yet been addressed.

It is important to stress that the methodology employed is not a worst case analysis, as is usually done for safety or regulatory compliance assessments, but it is an attempt to realistically evaluate the impacts expected from 1990's technology facilities at specific sites. In a few cases, however, when no reasonable alternative seemed possible, conservative values were used in the calculations.

The most important choices for the physical impact assessment of the nuclear fuel cycle concerned the definition of time and space boundaries. Due to the long half-life of some of the radionuclides, low-level doses will exist very far into the future. These low-level doses can add up to larger number when spread across many people and many years (assuming constant conditions). The validity of this type of modelling has been widely discussed. On one hand, there is a need to evaluate all the possible impacts if a complete assessment of the fuel cycle is to be made. On the other hand, the uncertainty of the models increases as the scale increases and the level of doses that are estimated, fall into the range where there is no clear evidence of resulting radiological health effects.

It has been shown that the distance at which the evaluation stops can have a large influence on the final costs, therefore, this is another important factor to be taken into account when defining the boundaries of an assessment. As in the case of long time periods, the uncertainty increases with the increase in the area considered.

The evaluation was completed using the conservative assumptions that:

- lifestyles affecting the level of external and internal radiation exposures would remain constant at current conditions;
- a linear dose-response relationship for radiation exposure, with no threshold at very small doses, does exist;
- all factors involving environmental transfer, human response to radiation, and survival rate of diseases will remain the same as today

If large distances and long time frames are included in the assessment of some fuel cycles and not in the assessment of others (due to lack of methodologies or data) the direct comparison of the results becomes a problem. It is for these reasons that the impacts estimated for the nuclear fuel cycle are presented in a time and space matrix. This form of presentation of results ensures that all the important impacts have been assessed and allows for the comparison of results in the appropriate categories. It also can be made clear that the uncertainty of the results increases with the scope and generality of the assessment.

The short-term category is considered to include immediate impacts, such as occupational accidents, medium-term includes the time period from 1 to 100 years and long-term from 100 to 100,000 years. The limit of 100,000 years is arbitrary, however this time scale does include the most significant impacts for all stages except high level waste disposal.

The impacts on the environment of increased levels of natural background radiation due to the routine releases of radionuclides have not been considered as a priority impact pathway. The most important impacts to the natural environment that could be expected would be the result of major accidental releases. This type of impact has been included in the economic damage estimates as the loss of land-use and agricultural products after a potential severe reactor accident. Possible long-term ecological impacts have not been considered at this time.

The final stage of economic valuation of the impacts has been challenging due to:

- the stochastic nature and delay time of the manifestation of radiological health effects at low-levels of exposure,
- the lack of contingent valuation studies directly applicable to radiologically-induced cancer and occupational health, and
- the applicability of the valuation methodology for long time span and global distances.

The economic data that is currently available for mortality and morbidity was utilised. Constant economic values were used for the global evaluation and the final results have been calculated using 3% and 10% discount rates, in order to attempt to take into account long term impacts.

14.2 Impact Results

14.2.1 Doses

Normal Operation

The total collective dose calculated for both the general public and workers, integrated for a time period of 100,000 years into the future, is 13 man.Sv/TWh taking into account all the stages of the nuclear fuel cycle. Over 95% of this dose is due to public exposures. The distribution of the public and occupational collective doses is presented in Table 14.1.

A closer look shows that the total estimated local collective dose is about 0.22 man.Sv/TWh and the total regional collective dose is 0.17 man.Sv/TWh, leaving over 95% of the public dose due to the global dispersion of certain radionuclides (essentially, C-14 and I-129). This global dose contributes more than 93% of the total collective dose for the fuel cycle, as is illustrated in Figure 14.1.

If the global doses assessment is not taken into consideration, the occupational doses contribute over 50% of the doses received (Figure 14.2).

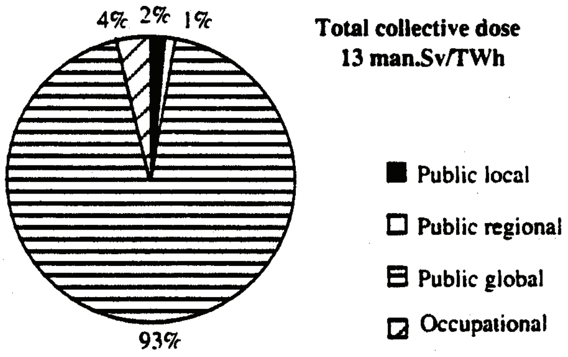


Figure 14.1 Distribution of the total collective dose

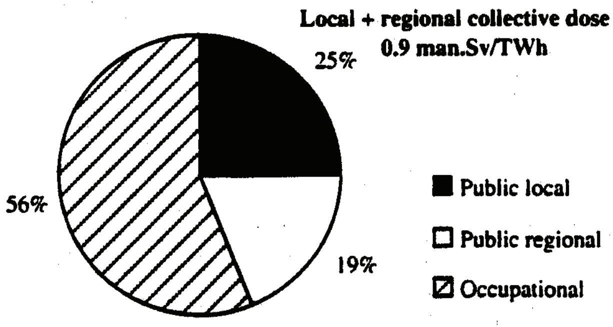


Figure 14.2 Distribution of the collective dose without global assessment

Table 14.1 Collective doses for the stages of the nuclear fuel cycle

Collective dose (man.Sv/TWh)	Public local	Public regional	Public global	Public total	Occupational	Total
Mining and milling	8.50E-02	9.17E-02	1.05E-04	1.77E-01	1.12E-01	2.89E-01
Conversion	2.40E-05	1.00E-05	9.53E-07	3.50E-05	2.29E-03	2.32E-03
Enrichment	2.22E-05	4.27E-06	3.90E-07	2.68E-05	8.33E-06	3.52E-05
Fuel fabrication	3.50E-07	8.86E-06	5.18E-09	9.21E-06	7.14E-03	7.15E-03
Electricity generation*	9.93E-04	1.71E-02	1.86E+00	1.88E+00	3.52E-01	2.23E+00
Decommissioning	1.45E-04	0	0	1.45E-04	2.16E-02	2.17E-02
Reprocessing	2.04E-04	6.07E-02	1.02E+01	1.03E+01	1.76E-03	1.03E+01
LLW disposal	1.27E-05	-	2.57E-02	2.57E-02	1.00E-04	2.58E-02
HLW disposal	1.36E-01	-	-	1.36E-01	6.00E-07	1.36E-01
Transportation	1.33E-03	0	0	1.33E-03	1.18E-03	2.51E-03
Sub-total	2.24E-01	1.70E-01	1.21E+01	1.25E+01	4.98E-01	1.30E+01

* excluding major accident

The reprocessing stage is the most important contributor to the total collective dose (including the global impact and the occupational doses), with 79% of the total dose (10.3 man.Sv/TWh). The second contributor is the electricity generation stage (17% of the total collective dose). But, if only the local and regional collective doses are considered (including occupational doses), the most important contributors become the electricity generation (0.37 man.Sv/TWh) and the mining and milling (0.29 man.Sv/TWh) stages. It can be seen that the enrichment stage is the least important.

For the workers, the total collective dose for all the different stages of the fuel cycle is about 0.5 man.Sv/TWh. The electricity generation and the mining and milling stages are the operations where the occupational collective dose is the most important (0.35 man.Sv/TWh and 0.11 man.Sv/TWh, respectively). It is estimated that the workers of the HLW disposal stage will be the least exposed group of workers in the fuel cycle, with 6E-7 man.Sv/TWh. However, this estimate is not based on actual data, being that such a facility does not exist at this time.

The collective dose is calculated taking into account the various exposure pathways resulting from the liquid and atmospheric releases (i.e. inhalation, ingestion, external exposure). The contribution of each pathway to the total is very dependent on the radionuclide considered. Table 14.2 presents the results organised by type of exposure pathway. For the public local and regional categories, it appears that the impact of the atmospheric and the liquid radioactive releases are of the same order of magnitude: 0.19 man.Sv/TWh for the atmospheric discharges and 0.21 man.Sv/TWh for the liquid discharges.

Table 14.2 Distribution of the collective doses by pathways in man.Sv/TWh

	Local		**Public local + reg.****		**Public global** **	
(man.Sv/TWh)	**direct * exposure**	**workers**	**gaseous**	**liquid**	**from food products *****	**C-14, I-129, Kr-85, H-3**
Mining and milling	0	1.12E-01	1.77E-01	1.54E-05	1.05E-04	0
Conversion	0	2.29E-03	3.35E-05	4.56E-07	9.53E-07	0
Enrichment	0	8.33E-06	2.63E-05	9.33E-08	3.90E-07	0
Fuel fabrication	0	7.14E-03	4.16E-07	8.79E-06	5.18E-09	0
Electricity generation	0	3.52E-01	1.23E-03	1.69E-02	2.24E-06	1.86E+00
Decommissioning	1.45E-04	2.16E-02	-	-	0	0
Reprocessing	0	1.76E-03	8.42E-03	5.25E-02	2.75E-03	1.02E+01
LLW disposal	0	1.00E-04	0	1.27E-05	0	2.57E-02
HLW disposal	0	6.00E-07	0	1.37E-01	-	-
Transportation	1.33E-03	1.18E-03	0	0	0	0
Sub-total	1.48E-03	4.98E-01	1.86E-01	2.06E-01	2.86E-03	1.21E+01

* direct exposure to the public (not due to releases)
** due to radioactive releases to the environment
*** due to food products produced within the regional area but consumed elsewhere

On a global scale, C-14 contributes the largest portion of the dose (about 10 man.Sv/TWh for La Hague and 2 man.Sv/TWh for Tricastin). It must be stressed that even though exposure to C-14 is responsible of more than 90% of the total collective dose, its global impact is the integration of very small individual doses over a very large time and space scale (100,000 years for an assumed constant global population of 10 billion people).

The release of C-14 for the whole nuclear fuel cycle represented in this report is about 8.4E4 MBq per TWh. At about 10 years after the release, the high end of the range of individual dose rates (2.3E-17 Sv/y per MBq released (IAEA, 1985)) was used to estimate an average individual dose of 2E-9 mSv/y per TWh. Based on these figures, if one additional reactor, such as Tricastin, were added to the nuclear park in France (an addition of about 5.7 TWh), 1.1E-8 mSv/y would be added to the average annual natural background dose of 2.4 mSv/y (1.2E-2 mSv/y of this is due to naturally-occurring C-14 (UNSCEAR, 1993)). The fact that this uncertain and insignificant additional risk to an individual ultimately dominates the assessment of the nuclear fuel cycle, opens the question of the adequacy of applying the monetary valuation methodology in a equal way to radically different levels of individual risk.

Accidental Situations

Transportation

Due to the very low probabilities of occurrence of accidents for the transportation of radioactive materials, the collective dose that results is less than 1E-7 man.Sv/TWh. This value is very small compared to the normal operation dose of 1.3E-3 man.Sv/TWh.

Reactor Accidents

In case of severe reactor accident, an indicative total collective dose for the population (for a radius of 3,000 km) for four accident scenarios has been estimated. The Table 14.3 presents the collective doses for the scenarios. The expected risk varies between 0.36 and 0.01 man.Sv/TWh. The impact of the most severe accident (ST2 - core melt with a massive containment breach) is a collective dose of about 300,000 man.Sv. This can be compared to the 560,000 man.Sv estimated for the USSR and European population as a result of the Chernobyl accident (UNSCEAR, 1993).

Table 14.3 Expected collective doses for a major reactor accident

Source term	Core melt probability (reactor.year^{-1})	Conditional probability	Collective dose (man.Sv)	Collective dose x probability (man.Sv)	Risk (man.Sv/TWh *)
ST2	5E-05	0.19	291,200	2.77	0.36
ST21	5E-05	0.19	58,300	0.55	0.073
ST22	5E-05	0.19	12,180	0.12	0.015
ST23	5E-05	0.81	1,840	0.07	0.0098

* 7.6 TWh/reactor.year for source terms from a 1200 MWe reactor

14.2.2 Health Effects

Normal Operation

The radiological health effects resulting from the normal operation of the nuclear fuel cycle are directly proportional to the total collective doses. The expected number of health effects were calculated assuming no lower threshold for radiological impacts, using internationally accepted data from ICRP60 (ICRP, 1991). Normalised by energy production the total number of expected health impacts are:

0.65 fatal cancers/TWh,
1.56 non-fatal cancers/TWh, and
0.13 severe hereditary effects/TWh.

These results include the global dose assessment estimates out to 1,00,000 years. Over 95% of these impacts would be expected to occur in the public domain.

To provide a perspective, the number of deaths due to cancer in the general European population that could be expected to occur due to the releases from the annual production of the an additional reactor (for example, Tricastin at 5.7 TWh/y), integrated over 100,000 years, is less than 1 (0.1). This value can be compared to the approximate 800,000 fatal cancers that are reported in Europe each year.

It is estimated that the production of 1 TWh will result in 0.019 deaths, 0.85 permanent disabilities and 261 working-days-lost (non-radiological health impacts) in the work force for the nuclear industry. The construction and the decommissioning of the reactor are the most important contributors to these values.

Accidental Situations

Transportation

The transportation of the radioactive materials between the different sites and the transportation of the materials involved in the construction and the decommissioning of the reactor result in accidents involving the general public. The number of expected health impacts is estimated to 3E-4 deaths and 1.5E-3 injuries per TWh. Assuming an additional annual production of 5.7 TWh, less than 1 death (0.02) can be expected per year. This is insignificant when compared to the nearly 10,000 deaths by road accidents occurring each year in France (INSERM, 1991). In accidental situations occurring during the transportation of hazardous radioactive materials such as UF_6, the toxicological health impacts estimated are even smaller (2E-9 deaths/TWh and 7E-5 injuries/TWh).

Reactor Accidents

The health effects from reactor accidents have been divided in two categories: the immediate health effects (deterministic effects) and the stochastic effects as cancers or hereditary effects. For the four accident scenarios considered in this study, only the two most severe accidents lead to deterministic effects, and deaths are expected only for the ST2 scenario (9 deaths expected, corresponding to a risk of 1.1E-5 deaths/TWh). For the stochastic effects, as for normal operation, they are considered to be directly proportional to the collective doses. Depending on the scenario, the number of expected fatal cancers varies from 1.8E-2 to 5E-4 per TWh based on 1 reactor.year of operation.

14.3 Monetary Valuation

14.3.1 Summary of Results

The final objective of this project is to report the monetary damages assessed for the impacts resulting from the releases of the nuclear fuel cycle activities. Except in the case of a severe accident, the damages are due to occupational and public health effects from radiological and non-radiological sources. Environmental impacts are taken into account in accidental situations where there is a market loss due to the damages. The costs are presented in a matrix of time and space that will allow for more direct comparisons to be made with other fuel cycles and studies that may have different assessment boundaries.

Although a comprehensive study of physical impacts has been completed, it must be stressed that the final costs should only be considered as a sub-total; it has not been possible to include the assessment of all possible impacts that should be included in a final total value. It is also important to stress that there has been very limited determination of the extent to which these impacts are to be considered externalities.

Table 14.4 (a) presents a summary of the costs of the physical impacts estimated for all stages of the fuel cycle, except for a severe reactor accident. The use of a discount rate changes the importance of the values in the different cells of the matrix, as can be seen in Tables 14.4 (b and c).

The sub-total of the cost presented for all the stages of the nuclear fuel cycle is about 0.1 mECU/kWh if the 3% discount rate is applied. The range that is found by varying the discount rates between 0% and 10% is between about 2.5 mECU/kWh and 0.05 mECU/kWh, respectively. The base load electricity generating costs in France are on the order of 35 - 40 mECU/kWh (50% of this value is due to investment costs) (CEA, 1994).

As has been stated, these results include the monetary valuation of the occupational health impacts. Over all, if no discount rate is used, the occupational impacts comprise of about 6% of the total cost. This proportion increases to over 78% when a 3% discount rate is applied, and over 96% with the 10% discount rate, due to the more immediate nature of some of the occupational impacts. These results, as well as the importance of the local, regional and global public doses are illustrated in Figures 14.3 and 14.4 for the three discount rates.

Table 14.4 The monetary valuation of physical impact for normal operation

a. Monetary valuation in mECU/kWh with no discount rate

DR =0%	**Short term**			**Medium term**			**Long term**			**Sub-total**
mECU/kWh	**local**	**regional**	**global**	**local**	**regional**	**global**	**local**	**regional**	**global**	
Mining and Milling	1.48E-02	0	0	3.23E-02	1.69E-02	1.94E-05	3.15E-04	1.82E-04	0	**6.45E-02**
Conversion	6.25E-04	0	0	3.43E-04	3.20E-07	1.77E-07	4.17E-06	1.54E-06	0	**9.74E-04**
Enrichment	1.18E-03	0	0	1.46E-06	1.00E-07	7.25E-08	3.91E-06	6.94E-07	0	**1.19E-03**
Fuel Fabrication	8.19E-04	0	0	1.07E-03	1.63E-06	9.64E-10	6.22E-08	1.09E-08	0	**1.89E-03**
Electricity Generation PWR 900										
- Construction	3.37E-02	0	0	0	0	0	0	0	0	**3.37E-02**
- Operation	1.31E-02	0	0	5.28E-02	3.19E-03	2.77E-02	1.23E-08	2.25E-09	3.19E-01	**4.16E-01**
- Decommissioning	0	0	0	1.70E-02	0	0	0	0	0	**1.70E-02**
Reprocessing	2.96E-03	0	0	2.98E-04	9.63E-03	1.60E-01	3.45E-06	1.67E-03	1.74E+00	**1.92E+00**
LLW Disposal	-	0	0	1.50E-05	0	1.24E-04	2.36E-06	0	4.66E-03	**4.80E-03**
HLW Disposal	-	0	0	8.98E-08	0	0	2.54E-02	0	0	**2.54E-02**
Transportation	3.55E-04	0	0	4.24E-04	0	0	0	0	0	**7.79E-04**
Sub-Total	**6.75E-02**	**0**	**0**	**1.04E-01**	**2.97E-02**	**1.88E-01**	**2.57E-02**	**1.86E-03**	**2.06E+00**	**2.48E+00**

b. Monetary valuation in mECU/kWh for 3 % discount rate

DR =3%	**Short term**			**Medium term**			**Long term**			**Sub-total**
mECU/kWh	**local**	**regional**	**global**	**local**	**regional**	**global**	**local**	**regional**	**global**	
Mining and Milling	9.94E-03	0	0	5.58E-03	2.90E-03	3.34E-06	7.52E-12	4.41E-12	0	**1.84E-02**
Conversion	4.18E-04	0	0	5.97E-05	5.26E-08	2.78E-08	1.01E-15	3.74E-18	0	**4.78E-04**
Enrichment	7.90E-04	0	0	2.54E-07	1.65E-08	1.25E-08	9.23E-18	1.68E-18	0	**7.90E-04**
Fuel Fabrication	5.48E-04	0	0	1.86E-04	2.81E-07	1.51E-10	1.50E-19	2.65E-20	0	**7.35E-04**
Electricity Generation PWR 900										
- Construction	3.37E-02	0	0	0	0	0	0	0	0	**3.37E-02**
- Operation	8.76E-03	0	0	9.20E-03	3.70E-04	1.84E-03	2.28E-10	4.18E-11	1.02E-04	**2.03E-02**
- Decommissioning	0	0	0	5.96E-03	0	0	0	0	0	**5.96E-03**
Reprocessing	1.98E-03	0	0	5.10E-05	1.28E-03	1.06E-02	6.42E-08	2.29E-06	5.53E-04	**1.45E-02**
LLW Disposal	-	0	0	2.61E-06	0	5.76E-06	1.04E-13	0	1.50E-07	**8.52E-06**
HLW Disposal	-	0	0	6.41E-09	0	0	0	0	0	**6.41E-09**
Transportation	2.38E-04	0	0	7.32E-05	0	0	0	0	0	**3.11E-04**
Sub-Total	**5.64E-02**	**0**	**0**	**2.11E-02**	**4.55E-03**	**1.25E-02**	**6.44E-08**	**2.29E-06**	**6.55E-04**	**9.52E-02**

c. Monetary valuation in mECU/kWh for 10 % discount rate

DR =10%	**Short term**			**Medium term**			**Long term**			**Sub-total**
mECU/kWh	**local**	**regional**	**global**	**local**	**regional**	**global**	**local**	**regional**	**global**	
Mining and Milling	5.20E-03	0	0	7.00E-04	3.63E-04	4.19E-07	8.48E-13	4.97E-13	0	**6.26E-03**
Conversion	2.19E-04	0	0	7.48E-06	6.28E-09	3.14E-09	1.13E-16	4.21E-19	0	**2.26E-04**
Enrichment	4.13E-04	0	0	3.18E-08	1.97E-09	1.56E-09	1.04E-18	1.89E-19	0	**4.13E-04**
Fuel Fabrication	2.87E-04	0	0	2.33E-05	3.55E-08	1.71E-11	1.69E-20	2.98E-21	0	**3.10E-04**
Electricity Generation										
PWR 900										
- Construction	3.37E-02	0	0	0	0	0	0	0	0	**3.37E-02**
- Operation	4.58E-03	0	0	1.15E-03	2.67E-05	1.18E-04	2.57E-11	4.71E-12	1.15E-05	**5.89E-03**
- Decommissioning	0	0	0	7.94E-04	0	0	0	0	0	**7.93E-04**
Reprocessing	1.04E-03	0	0	6.29E-06	1.17E-04	6.79E-04	7.24E-09	2.58E-07	6.23E-05	**1.90E-03**
LLW Disposal	-	0	0	3.26E-07	0	8.44E-08	1.53E-15	0	2.19E-09	**4.13E-07**
HLW Disposal	-	0	0	1.12E-10	0	0	0	0	0	**1.12E-10**
Transportation	1.31E-04	0	0	9.18E-06	0	0	0	0	0	**1.40E-04**
Sub-Total	**4.56E-02**	**0**	**0**	**2.69E-03**	**5.07E-04**	**7.97E-04**	**7.26E-09**	**2.58E-07**	**7.38E-05**	**4.97E-02**

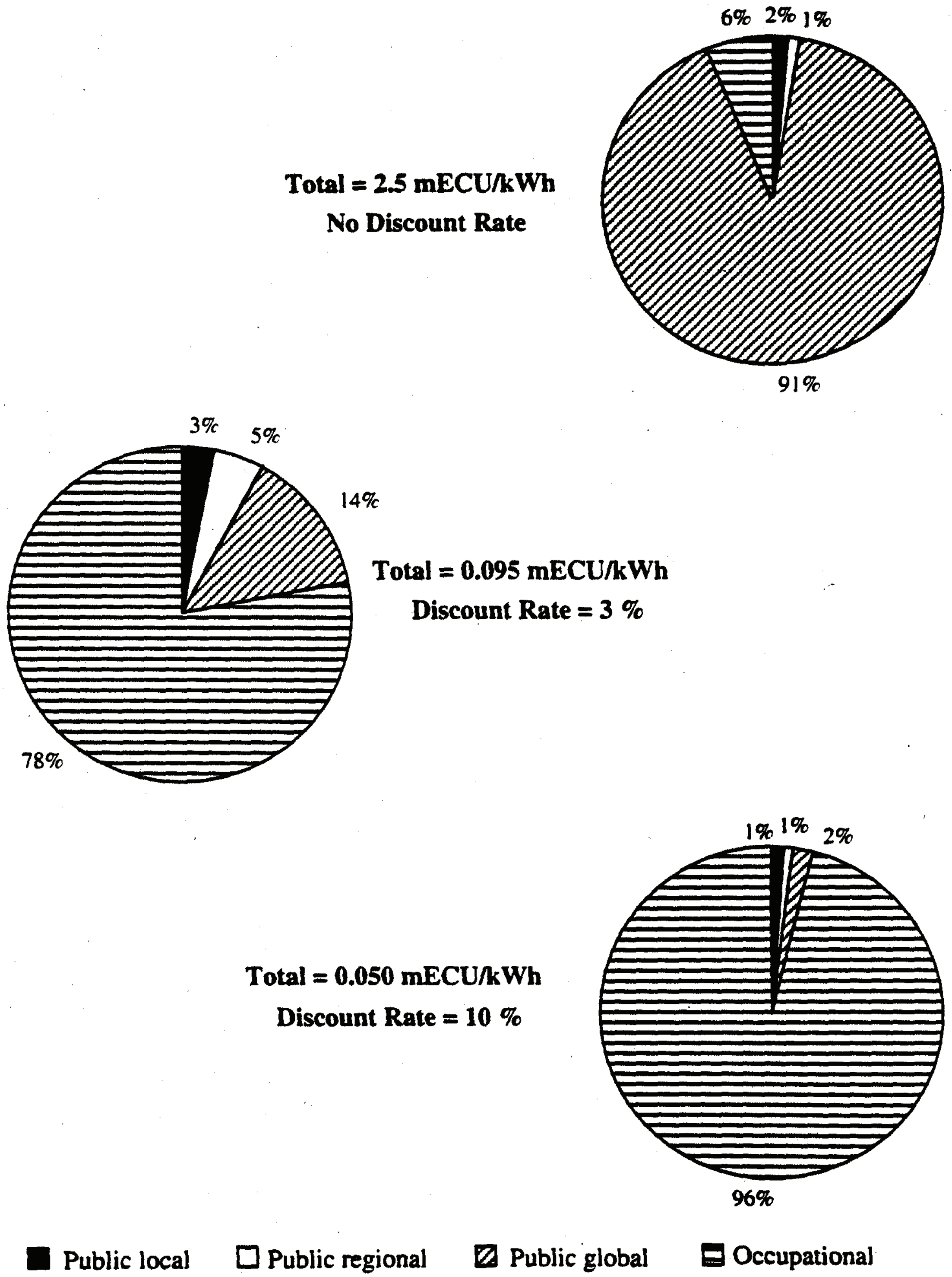
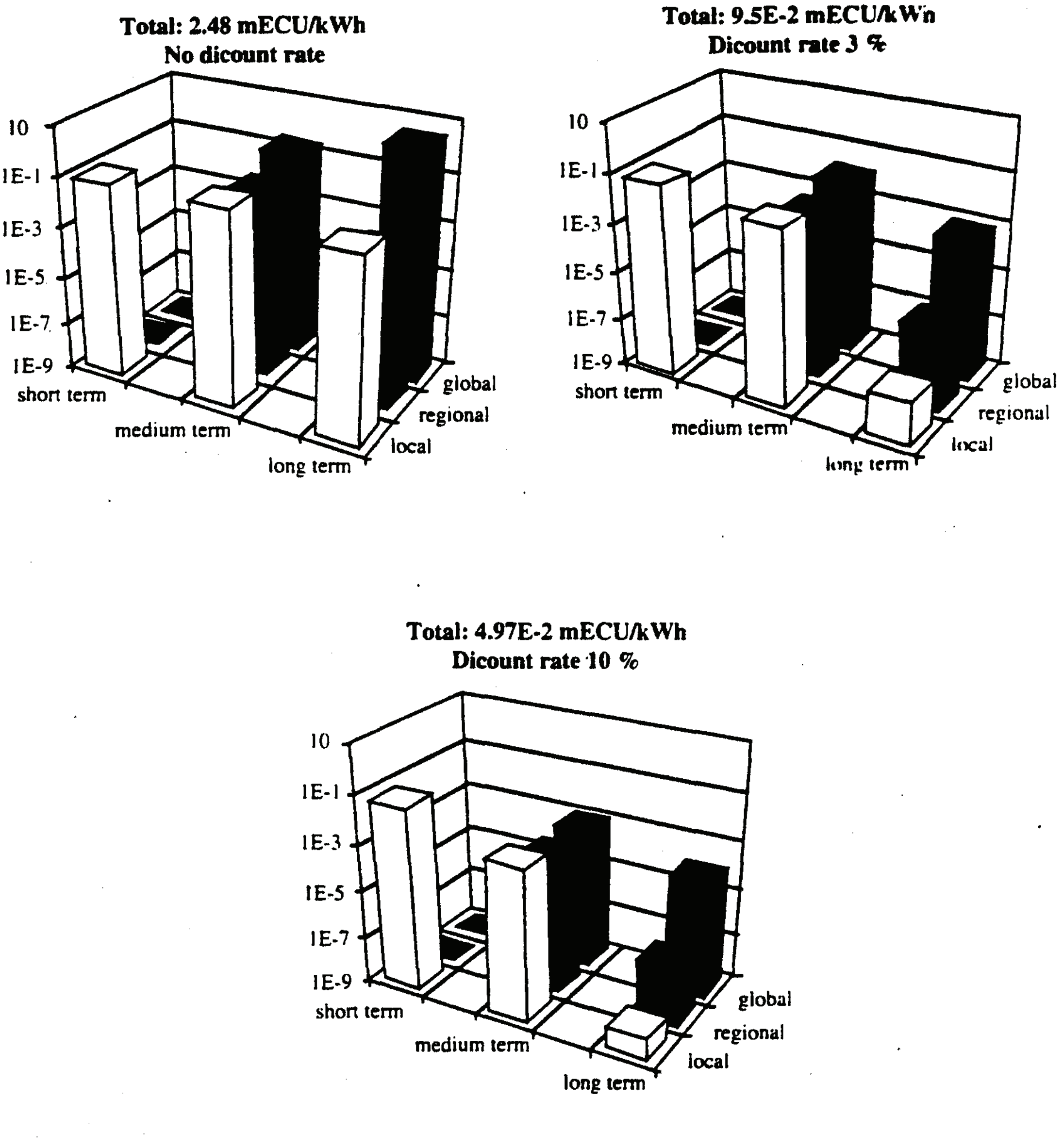


Figure 14.3 Distribution of the costs for the 0%, 3% and 10% discount rates



Total: 2.48 mECU/kWh
No dicount rate

Total: 9.5E-2 mECU/kWh
Dicount rate 3 %

Total: 4.97E-2 mECU/kWh
Dicount rate 10 %

Figure 14.4 Distribution of the costs for the 0%, 3% and 10% discount rates with time and space (log scale)

The results of the consequence assessment for the four accident scenarios assessed at a hypothetical PWR site in the centre of western Europe are presented on Table 14.5. The results in Table 14.6 present the calculations when the probabilities of occurrence of the accidents are taken into account. These results are considered to be indicative of the impacts that would be found using a risk-based methodology. The largest release (ST2, approximately 10% of the core) is considered to be indicative of a core melt accident followed by a massive containment breach results in a 0.1 mECU/kWh cost. The risk for the smallest release (ST23, approximately 0.01% of the core), that would be expected to occur after a core melt if all the safety systems operate as planned, is estimated to be about 0.002 mECU/kWh. The other two source terms have been analysed to illustrate the sensitivity of the results.

Table 14.5 Monetary valuation for four possible source terms for a severe nuclear reactor accident

Source term	Total cost health effects (MECU)	Total cost food bans (MECU)	Total cost evac. + reloc. (MECU)	Sub-total cost (MECU)
ST2				
local	11,044.1	824.0	1,515.2	
regional	43,059.0	26,809.6	-	
total				**83,252**
ST21				
local	1,525.2	330.7	98.1	
regional	9,318.6	5,820.0	-	
total				**17,093**
ST22				
local	237.5	86.0	13.5	
regional	2,023.7	978.0	-	
total				**3,339**
ST23				
local	39.6	13.7	10.9	
regional	303.2	63.6	-	
total				**431**

Table 14.6 Results of accident analysis for 4 different scenarios including public health effects and costs of countermeasures

Source term	Core melt probability (reactor.year^{-1})	Conditional probability	Total cost (MECU)	Cost x probability (MECU)	mECU per kWh *
ST2	5E-05	0.19	83,252	0.790	0.104
ST21	5E-05	0.19	17,093	0.162	0.021
ST22	5E-05	0.19	3,339	0.032	0.0042
ST23	5E-05	0.81	431	0.017	0.0023

* 7.6 TWh/reactor.year for source terms from a 1200 MWe reactor

14.3.2 Discussion

Normal Operation

The assessment of the priority impacts for all stages of the nuclear fuel cycle have been completed. A key factor in the interpretation of these results are the dimensions of time and space because the choice of boundaries can have a profound effect on the final result. Before applying the results of this study, the context and the comparative framework must be clearly defined so that the correct range of results are used for the specific decisions to be made, otherwise, false conclusions may be drawn.

Without application of a discount rate to the final results, it can be seen that the total public health costs from the local, regional and global impacts contribute 94% of the 2.5 mECU/kWh sub-total, the remaining 6% due to occupational impacts. The reprocessing stage of the fuel cycle is the largest contributor at 1.9 mECU/kWh (about 77% of sub-total 2.48 mECU/kWh), and the releases from the electricity generation stage contributes about 14%. In both cases, this has been a result of the global assessment of the C-14 releases. As has been discussed earlier in this chapter, before the costs of the global long-term assessments should be used in decision-making, important methodological issues need to be resolved regarding the validity of treating extremely different levels of individual risk in the same way and valuing far future impacts.

On the local and regional scale, the atmospheric and liquid releases are equally important. Most of the atmospheric pathway impacts result from the dispersion of radon from the mining and milling stage, and for the liquid release pathways, the high level waste (HLW) disposal stage is important. Being that the important potential impacts for high level waste disposal occur in the far future, and if a discount rate is not used, far future impacts are being treated in the same manner as the impacts that may occur today. If any discount rate is applied to the HLW costs, they are reduced to essentially zero. When the public reaction to the radioactive waste debate is noted, the key issue of the applicability of the current methodology in the assessment of the external costs of the HLW disposal stage is raised.

Because there has been no general consensus of the best discount rate to use to value future impacts, the range from 0% to 10% has been implemented in this study. The rate of 3% has been chosen as the most likely, or central value. With the application of a 3% discount rate to the whole fuel cycle, the most important contributor becomes the reactor construction phase (35%) because discounting does not reduce the very short term non-radiological impacts. The next most important contributors are the operation phase of electricity generation and mining and milling (21% and 19%, respectively), also due to the importance of the short term occupational health impacts.

The cost contribution from the reprocessing stage changes from 77% of the sub-total to 15% with the discount rate of 3% (Table 14.4 (b)), to as low as 4% when the 10% discount rate is used (Table 14.4 (c)). This is due to the fact that the largest portion of the impacts occur in the long term and therefore are greatly reduced if any discount rate is used.

At the top range of the discount rates that might be used in the valuation methodology of long term impacts (10%), the cost from the construction of the reactor rises to 68% of the sub-total, followed by mining and milling (13%) and operation of the reactor for electricity generation (12%). The most dramatic drop in cost can be seen for the waste disposal operations where the values become essentially zero.

Accidental Situations

Transportation

The contribution of risk of transportation accidents to the overall costs calculated for the nuclear fuel cycle can be considered to be negligible (0.00035 mECU/kWh). This is largely due to the fact that the most dangerous materials to be transported travel the shortest distances (about 5 km).

Reactor Accidents

Two general categories of accidental releases have been addressed during this phase of the work: a core melt accident with a massive containment release and a core melt accident without a breach of containment. Being that these results are considered to be only indicative, they have not been included in the 2.5 mECU/kWh sub-total, but if they are added, there is an increase of about 5%. Although it is acknowledged this assessment is only indicative, its results are broadly in accord with more comprehensive assessments.

For three source terms considered to be a result of a massive containment breach (ST2, ST21, ST22), the health effects costs contribute about 65% of the sub-total (before the probability is applied). This partition increases to 80% for the smallest release scenario, but it must be noted that the cost for ST23 is less than 1% of the cost for ST2. After the probability of occurrence is taken into account, the range in results spans 2 orders of magnitude. Other social costs, such as risk aversion, have not been quantified at this time.

The US ORNL team (ORNL, 1993) assessed the costs of severe nuclear reactor accidents using the same risk-based methodology and type of accident consequence computer code (MACCS). Two types of accidents at two sites were included in their assessment. The results presented in the ORNL draft report are 0.06 mills/kWh for the Southeast site (SE) and 0.006 mills/kWh for the Southwest site (SW). In addition, the US team included the cost estimates for waste disposal, loss of utility assets, utility site clean-up, replacement power, and decommissioning after the accident. These additional costs will contribute about 0.04 mills/kWh, which would about double the SE site accident costs and dominate the SW site accident costs.

A Probabilistic Safety Assessment (PSA) for modern UK reactors completed a comprehensive assessment of 12 possible core melt accident scenarios and their associated probabilities (Wheeler *et al*, 1994). Another accident consequence computer code (CONDOR) was used to estimate the same costs that considered in COSYMA and MACCS. The cost of a severe accident taking into account all the scenarios was reported to be 0.0001 p/kWh or about 0.001 mECU/kWh. In a nuclear utilities group report to the UK government presenting these results, it was suggested that this value be increased an order of magnitude to 0.01 mECU/kWh for the sake of conservatism.

The range of costs that are found using this type of methodology, as shown by this assessment, the US team, and Wheeler and Hewison (Wheeler *et al*, 1994), fall within the range of 0.01 to 0.1 mECU/kWh. If this range of costs is accepted as the portion of the severe accident costs attributable to health effects and countermeasure implementation, further effort can be made to assess the source of other social costs that should also be included.

Pearce (Pearce *et al*, 1992) has also concluded that the externality adders for health effects costs due to a severe nuclear accident assessment would be negligible after assuming an accident probability considered correct for the type of technology that would be built in the UK today (one in a million chance (1E-6) per reactor year).

As with external costs of high level waste disposal, there is a great difference between the risks calculated by technical experts and the public's perception of the probability of occurrence and the magnitude of the risks of potential reactor accidents. If these social costs are to be included, more work is needed to develop methodologies to incorporate influence of risk aversion and risk perception. Preliminary proposals on possible mechanisms to estimate risk aversion have been proposed by Krupnick, Markandya and Nickell (1993), however, at this time, insufficient data is available to complete the estimates.

14.4 Uncertainty

The level of uncertainty associated with the results is due to the scenarios defined, the models applied, the input data used and the lack of available information for some pathways. Each part of the methodology contributes to the overall uncertainty. For example, by using generalised transfer coefficients and assumptions, in most cases, the situations that exist at the extremes have not been taken into account.

The estimates of uncertainty that were presented in the methodology are based on expert judgements and the range of possible input values. It is not possible to determine the uncertainty of the final results by simple multiplication of the general uncertainties at each stage of the calculation. As a general rule, it is possible to assume that the longer the time span and/or the larger the region considered in the model, the larger the uncertainty in the model and the input data.

A detailed uncertainty analysis of the results has not been carried out but indications of the levels of uncertainty have been completed and were discussed in the results section. Using a "back of the envelope" propagation of the error method, it has been estimated that for the 67% confidence interval (Hibbs, 1994), the results are considered to be correct within an order of magnitude. The exception to this is for the estimates of human exposure and dose conversion where an uncertainty of an order of magnitude can been indicated in certain extreme individual cases.

A lower level of confidence can be assigned to the results of the global assessments for C-14, H-3, I-129 and Kr-85, due to the extremely general models that are used and the propagation of very small doses over a large population for very long periods of time. Some far-reaching assumptions were taken. The confidence in these estimates are probably greater than an order of magnitude except in the case of C-14, where the global carbon cycle is quite well known.

The estimates of the doses for the waste disposal stages are also considered to have a greater factor of uncertainty. The CEC PAGIS study (CEC, 1988) completed a more comprehensive uncertainty analysis for high level waste disposal. For the normal evolution scenario, an uncertainty of about 3 orders of magnitude was reported for the results of the granite disposal option in France calculated for a time period of millions of years. The low-level disposal site assessment employs the same type of hydrogeological models and exposure assumptions but the time scale of the possible impacts is quite shorter. Due to the different time scale, it is considered that the maximum uncertainty would be 3 orders of magnitude, but it is likely to be smaller.

For estimation of the uncertainty of the accident assessment results, one must consider the methodology for the assessment of the consequences, the probabilities that have been assigned, and the gaps in information and the methodology. It can be estimated that the uncertainty of the accident assessment results could range from a factor of 2 to as large as 3 or 4 orders of magnitude.

14.5 Comparison with other Studies

For the most part, early comparative risk assessments of different fuel cycle options concentrated on deaths and injuries as the indicators for impacts. In 1988, O. Hohmeyer published a report on the social costs of energy consumption (Hohmeyer, 1988). This was followed by a German-American workshop in 1990 on the external environmental costs of electric power (Hohmeyer, 1991) and the "Pace University Report" on the environmental costs of electricity (PACE, 1990). The results from these studies included impacts that had not been addressed in previous studies, and the emphasis on social costs required that different impacts pathways be considered. The use of money as an impact indicator was introduced at this time. One of the major disadvantages of these studies was that the boundaries of the assessments and methodologies applied varied between the different fuel cycles, therefore it was difficult to objectively compare the final results. The ExternE project set, as one of its main objectives, the goal of analysing different fuel cycles within the same consistent methodological framework in order to allow for direct comparison between fuel cycle options. Since the start of this project, a number of other projects have been initiated on the international and national levels.

The following table shows the results for nuclear fuel cycle assessments of the EC and US partners in this project along with the other main studies in the field. Direct comparison of these results are not really possible due to the different approaches and coverage of the cycle, but it is useful to illustrate the context in which the ExternE project results will be placed.

		Total cost (mECU/kWh)	Cost without accident (mECU/kWh)
CEPN	**(DR=0%)**	2.5 - 2.6	2.5
	(DR=3%)	*not completed*	0.1
	(DR=10%)	*not completed*	0.05
ORNL 1993	**mid value SE site**	0.3	0.2
	mid value SW site	0.2	0.2
Pearce *et al* 1992		0.8 - 1.8	0.5 - 1.2
Friedrich & Voss 1993		0.1 - 0.7	0.1 - 0.4
Pace 1990		29.1	6.1
Hohmeyer 1991		14.6 - 88.2	*not done*
Hohmeyer 1988		5.0 - 50.4	*not done*

The large range of results can be attributed to:

(1) the different number of fuel cycle stages included in each assessment,
(2) the methodology for the valuation of the health impacts,
(3) the discount rate applied,
(4) the inclusion of a global physical impact assessment, and
(5) the methodology and assumptions used for the assessment of severe nuclear accidents.

US DOE Draft Report 1993

At first glance, the results of the US team (Oak Ridge National Laboratory) (ORNL, 1993) and the European team (CEPN) appear to be an order of magnitude apart. The methodology used by both assessments is essentially the same. The main reason for the difference is due to the definition of the fuel cycle and the boundaries of the assessment. The US assessment does not include the reprocessing stage (it does not exist in the US) and the conversion, enrichment, fuel fabrication and low level waste disposal stages (they were not considered as priority stages for the first phase of the project). Both teams presented an evaluation of the physical impacts of the high-level waste disposal but the EC team has added the valuation of this stage. In an effort to be consistent with the other EC fuel cycle assessments, the EC nuclear fuel cycle has expanded the physical boundaries of the assessment to the 1000 km (regional) and global dimensions, which has also contributed to the increased values seen in the results. The technologies and sites represented in the two assessments have different characteristics which also adds to the variation in the physical impact results.

When the comparable results from CEPN are summed for the relevant stages (public local, public regional and occupational costs, including accidents) with a 3% discount rate, the subtotal ranges from 0.08 to 0.22 mECU/kWh. This is essentially the same as the ORNL results. The severe accident assessment methodology was the same for both studies. The range of results in the US study is 0.1038 mills/kWh at the Southeast site and 0.0545 mills/kWh at the Southwest site, which is within the same order of magnitude as the indicative CEPN results. The US results integrate two possible types of accidents into one risk figure and include the additional cost estimates of waste disposal, loss of utility assets, utility site clean-up, replacement power, and decommissioning. These additional costs contribute about 40% and 75% of the total costs reported for the Southeast and Southwest accident assessments, respectively.

Pearce et al 1992

The Pearce *et al* report (Pearce *et al*, 1992) includes mortality, morbidity, health effects due to severe accidents and greenhouse gases emissions for the nuclear fuel cycle. A range of values are presented for morbidity and severe accidents. Radiological morbidity values are presented as a function of the cost per unit collective dose (man.Sv). The recommended range of VSL ranges from 1.4 to 2.4 MECU. The report concluded that the health effects due to a severe nuclear accident would be negligible after assuming a probability of one in a million chance (10^{-6}) of an accident per reactor year for the technology that would be built in the UK today. However, different attempts at adding a risk aversion factor, to take into account the social reaction of the public, produced estimates that ranged from 0.02 to 0.05 p/kWh but possibility as high as 0.3 p/kWh.

Friedrich and Voss 1993

The external costs of health effects presented by Friedrich and Voss (Friedrich *et al*, 1993) are for normal operation of the nuclear fuel cycle and assume a value of a statistical life of US $2.9 million. The "rough estimate" of the costs of a hypothetical accident assessment, based on the results of a US Nuclear Regulatory Commission report that were adjusted to conditions in Germany, ranged from 0.01 and 0.07 pf/kWh.

Pace 1990

The results of the Pace University (PACE, 1990) are divided into routine operation impacts, severe accidents, decommissioning, and waste disposal. The damages due to severe accidents account 79% of the costs, leaving less than 4% from normal operation impacts and 17% due to waste disposal. The Pace study defined the VSL as US$ 4 million.

The cost from normal operations of the nuclear fuel cycle reported by Pace is about 4 times higher than the CEPN estimate, if the global doses are not taken into account. This is mostly due to Pace's higher occupational health estimates (6 times higher) which is most likely due to the use of data from ageing nuclear power plants. The total decommissioning costs reported by Pace (5 mills/kWh) are likely to be an overestimate. The CEPN estimate of 0.017 mECU/kWh for decommissioning costs takes into account the occupational impacts and the doses to the public from material transport. It does not include the total cost of decommissioning the facility because it is considered to be internalised.

The accident assessment in the Pace study assumes that the probability of an accidental release is 8 times greater that the largest probability currently assumed in the CEPN assessment. The total cost of the accident in the Pace study is based on the Chernobyl accident, which is not considered to be in any way representative of what would happen in reactors built and operated in western countries. In addition, the international population dose assumed in the calculation is about 4 times greater than the world-wide dose estimated by UNSCEAR in its 1988 report. With that scenario, the Pace study estimates a total cost of the accident at 7 times higher than the highest total cost estimate presented by CEPN and a final risk value of 23 mECU/kWh compared to the highest risk estimate of 0.14 mECU/kWh per reactor year from CEPN. In an interview published in IRP Report (Hibbs, 1994) it was acknowledged that the estimates made at this time may have been overstated.

Hohmeyer 1988 and 1991

The costs resulting from human health impacts published by Hohmeyer (Hohmeyer, 1988) only include the assessment of an accident. The basis of the calculations are the same as was used in the Pace study. The intention in that report was to estimate the total costs that would be incurred by Germany (only the western part at the time of publication) if an accident occurred. The monetary valuation per cancer incidence used was 750,000 DM.

In order to evaluate the possible range of results, various estimates depending on the degree of conservatism was adopted for each stage in the simple calculation. The hypothesised release fraction of the core was varied by a factor of 50, the population density and cancer incidence factor were varied by factors of 20, and the probability of an accident was varied between 5E-05 and 5E-04. As a consequence, the results range from 0.00003 to 5.55 DM/kWh. The final estimate reported based on assumptions from the Chernobyl accident multiplied by 10 to account for the greater population density to be expected in Germany. This was reported as a minimum damage range of 0.012 to 0.12 DM/kWh.

In 1991, Hohmeyer published a revision of the first estimates for the costs of severe nuclear accidents in a paper on wind energy (Hohmeyer, 1991). The explanation of the causes for the increase in costs to between 15 and 88 mECU/kWh were not included in the paper.

14.6 Conclusions

The systematic assessment of all the stages of the nuclear fuel cycle with a common methodology and boundaries has provided a good base of information with which to understand the impacts of fuel cycle and a preliminary assessment of the external costs due to these impacts. At this stage, no definitive evaluation has been made to determine to what extent the costs presented in this report are externalities.

In presenting the results, care has been taken to indicate that the "sub-total" costs are not intended to represent the absolute total of all the impacts possible. Within the resources available for this project, the priority impact pathways have been analysed and the most important impacts are included.

In attempt to include all impacts within a rather large time and space scale, the limits of valid assumptions have been stretched in order to be as complete as possible in the physical impact assessment. Current day conditions have been assumed to remain constant for 100,000 years - a truly unlikely event. However, with these assumptions it was possible to complete the assessment for the long-lived radionuclides. It has been illustrated in this assessment that the choice of the time and space boundaries has an important influence on many aspects of the final results and must be considered before application of these results in a decision making framework.

No thresholds have been assumed in the calculation of the response to the doses received, so in many cases, the average individual doses to the public fall into a highly uncertain area of the dose-response relationship. The generally accepted collective dose approach, which integrates the average individual doses over the total population to be considered, was implemented. With this approach, the magnitude of the individual risk is masked when the results are presented. The most obvious drawback of this approach has been seen in the evaluation of the long-term global impacts of C-14, where the very small individual doses are summed to a large value over time and space. However, without this assessment, an important part of the overall potential physical impacts from the nuclear fuel cycle would not have been complete.

The future research recommendations that would improve on the foundation set by this report fall into the following categories: assessment of uncertainty, determination of external costs, assessment of major accidents, determination of the validity of integrating small individual doses over large populations for the sake of risk assessment, and development of appropriate methodologies to deal with large spans of time and space.

For the most part, the estimates of cost that have been reported are not accompanied by a rigorous estimate of the uncertainty. The uncertainty has been addressed in a more qualitative way due to the lack of resources to perform a detailed analysis and in many cases the lack of information. Further work, using the data and models that have been developed during the course of this project, would provide more quantitative estimates of uncertainty.

More effort should be made to determine the portion of the reported costs of the physical impacts, that are external costs for the nuclear fuel cycle. Public health impacts can clearly be considered external costs, but it is not clear as to whether occupational impacts should be totally included. The assessment of nuclear accidents has not yet included an evaluation of the liability and international insurance programmes that currently exist. These questions could be answered with some direct effort.

The assessment of a potential severe nuclear reactor accident was based on a risk-based approach. This methodology has not been accepted by everyone, however, it has been judged as an adequate basis for the calculation of the physical impacts within a range of uncertainty. This does emphasise the need for further methodological work to determine the additional social impacts and costs that have not been included in this type of approach.

Although there are limitations and uncertainties in the methods used for the assessment of the physical impacts, the key methodological issues that remain are for the monetary valuation stage. Before the monetary values of the impacts from the nuclear fuel cycle can be considered to be external costs the following issues must be addressed:

> If the same monetary valuation methodology is used for the evaluation of very small (and quite uncertain) individual risks to a large population and larger individual risks to a smaller population, does the final result really demonstrate the proper weighting of the real risks? Should occupational (voluntary) risks be valued in the same manner as risks to the general public (involuntary risks).
>
> If the use of a discount rate is not considered to be acceptable for the evaluation of far future impacts, what should be used in its place? The results of this phase of the project should be reviewed in order to determine how to provide a good representation of present day and far future risks.
>
> How can a method realistically incorporate the societal perceptions in terms of time and space keeping in mind the need for society to balance between the options available? For example, if C-14 is released today, it is diluted and results in low individual risks with no future disposal problems. If the releases are captured, waste repositories must be maintained causing increases in occupational risks and large local population risks in the far future.
>
> How can the aversion of certain risks be equitably included in the assessment of external costs? This problem is clearly illustrated in the differences between expert and public perceptions of the risks of potential nuclear accidents and high-level waste disposal.

Even with these unresolved issues, the study has made important advances in reporting the physical impacts and monetary valuation of these impacts in a manner consistent with other fuel cycles. In addition, this study has identified many remaining uncertainties in the methodology, and highlighted important parameters that should be considered in the decision making process.

14.7 References

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