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COST-EFFECTIVENESS ANALYSIS OF COUNTERMEASURES USING ACCIDENT CONSEQUENCE ASSESSMENT MODELS

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Abstract — In the event of a large release of radionuclides from a nuclear power plant, protective actions for the population potentially affected must be implemented. Cost-effectiveness analysis will be useful to define the countermeasures and the criteria needed to implement them. This paper shows the application of Accident Consequence Assessment (ACA) models to cost-effectiveness analysis of emergency and long-term countermeasures, making use of the different relationships between doses, contamination levels, affected areas and population distribution, included in such a model. The procedure is illustrated with the new Melcor Accident Consequence Code System (MACCS 1.3), developed at Sandia National Laboratories (USA), for a fixed accident scenario. Different alternative actions are evaluated with regard to their radiological and economical impact, searching for an 'optimum' strategy.

INTRODUCTION

The serious consequences that a major accident at a nuclear power plant could cause are specially important for the urban environment. The need to implement countermeasures for the protection of the population requires that decision makers balance the large economic costs that those actions could involve, together with the social disruption that they may imply, and the potential health effects that can be avoided. Accident Consequence Assessment (ACA) models can constitute a powerful tool to assist in arriving at such a balance, as they give the different relationships between contaminated areas, population distribution and radiological effects, apart from simulating the economical impact of countermeasures and dose reduction effectiveness. Political and social considerations must also be considered, but these are currently not amenable to numerical analysis and will not be considered here.

There are three main inputs that will govern the estimated consequences of an accident:

(i) The magnitude and characteristics of the source term.
(ii) The site characteristics.
(iii) The protective actions criteria.

By selecting a source term that will spread radioactive products over a given site, it is then possible to analyse the appropriateness of different countermeasures implementation criteria to minimise the impact of the accident. But the consequences will be both radiological and economic, and it will not be possible to neglect any of them. Consequently, it is necessary to search for the less harmful criterion. This is the objective of cost-effectiveness analysis that this paper tries to illustrate.

A cost-effectiveness analysis of countermeasures is described using the MELCOR Accident Consequence Code System (MACCS 1.3)[1], developed at Sandia National Laboratories (USA), as a part of the new, integrated system of severe accident risk-assessment codes for the US Nuclear Regulatory Commission. MACCS incorporates improved models for atmospheric transport, dispersion and deposition, emergency response, radiation dosimetry, radiological health effects, exposure pathways, and economic consequences. MACCS is structured to facilitate performing uncertainty and sensitivity analyses, thus being appropriate for cost-effectiveness studies.

ACCIDENT DEFINITION

As a basis for the analysis, an accident scenario is considered by assuming the following circumstances:

(1) An end-of-cycle core inventory for a 3412 MW(th) Pressurised Water Reactor (PWR), calculated[2] with the SANDIA-ORIGEN code.
(2) A TMLB'-δ accident sequence, equivalent to a transient initiated by a loss of off-site AC power, with failure of the power conversion system and the safety engineering features, ending with a containment failure due to

overpressure. The release fractions and other source term characteristics, shown in Table 1, are taken from NUREG-0773[3].

(3) Dry deposition velocities of 0.005 $m.s^{-1}$ for iodine, 0.001 $m.s^{-1}$ for other isotopes, and zero for noble gases.
(4) New York City meteorological data. Indian Point population and economic data in the MACCS data set[4].
(5) Radiation protection factors as shown in Table 2. Note the good shielding assumed for sheltered people, with a protection factor of 0.08 for groundshine, representative for brick houses with basement.
(6) An emergency response, consisting of a phased evacuation by people living inside the circle of 6 km radius around the reactor; starting 30 min before the release within the inner circle of 2 km, and continuing 1 h and 2 h later inside the annulli between 2-4 km, and 4-6 km respectively. A radial evacuation is assumed at a speed of 5.55 $m.s^{-1}$ (20 km per hour). A shelter zone between 6 and 10 km is defined. Beyond 10 km, two relocation criteria are followed: a normal relocation 1 day after the arrival of the plume in those zones where the 24 h groundshine external gamma dose to the bone marrow exceeds 0.1 Sv; and a hot spot relocation 6 h after the arrival of the plume when the projected groundshine dose exceeds 0.5 Sv in 24 h.

Table 1. Fission product release characteristics.

Accident sequence:	PWR, TMLB'-δ
Estimated probability:	2×10^{-6} per reactor-year
Time of release:	2.5 h
Duration of release:	0.5 h
Energy of release:	5×10^{7} W

Fractions of core inventory released

Isotope group	Release fraction
Xe-Kr	1.0
I	0.31
Cs-Rb	0.39
Te-Sb	0.15
Ba-Sr	0.04
Ru	0.02
La	0.002

(7) A long-term protective actions response, consisting of an intermediate phase relocation when the groundshine dose to the bone marrow or the re-suspension dose to the lungs exceeds 0.05 Sv for the first 30 days, and a long-term phase relocation, followed by decontamination or interdiction, when any of the above mentioned doses exceeds 0.25 Sv for the first 30 years. With regard to the disposal of agricultural products, the code has fixed values for the criteria adopted, and no specific consideration will be made.
(8) Three decontamination levels are considered, corresponding to decontamination factors of 3, 15 and 20 respectively, with estimated costs[5] of 2600, 6900 and 7400 US dollars per person living in urban areas. All other economic considerations are taken from Burke's work[5].

EMERGENCY PLAN ANALYSIS

Estimated consequences for the base can be summarised in early and latent health effects and economic impacts. Health effects in MACCS are estimated according to recent investigations[6]. Early health effects can serve as a measure of the effectiveness of the emergency plan, whose economic impact will be relatively modest when compared with that of long-term protective actions. Therefore, cost-effectiveness analyses of short-term protective actions should be made in terms of radiological cost.

It is interesting to evaluate how damage is distributed with distance, in order to investigate modifications to the emergency response that could make it more effective. As a measure of damage, Figure 1 represents the mean values of acute total dose to the bone marrow under the plume centreline, for the base case studied, as a function of distance. As can be seen, early evacuation within a range of 2 km around the reactor would be a very effective measure in reducing damage. From 2 up to 6 km, the evacuation takes place once the plume has been released, and the effect of an increase in dose is observed. Sheltering up to 10 km acts as an effective dose reduction measure, and from this distance on, the relocation criterion does not avoid a greater exposure.

Table 2. Radiation protection factors used in the base case.

Type of activity	Cloud shielding factor	Inhalation protection factor	Skin protection factor	Ground shielding factor
Evacuation	1.0	1.0	1.0	0.50
Normal	0.75	0.75	1.0	0.33
Sheltered	0.50	0.5	1.0	0.08

Modifications to the base case emergency plan have been studied for five different aspects, summarised in Table 3. All the analyses have been made replacing only one parameter each time, and setting the remainder equal to the base case values. Moreover, Table 3 shows the mean value of prompt fatalities obtained in each case.

The effect of extending the evacuation radii is shown in Figure 2, where the Complementary Cumulative Distribution Functions (CCDF) for prompt fatalities are displayed. As Figure 2 and Table 3 indicate, the first enlargement of the evacuation zone up to 8 km, with the early evacuation (before the release) within the 4 km circle, is a very effective countermeasure, since people living between 2 and 4 km will also escape from the plume, as did the base case people within 2 km. However, an enlargement of the zones where the time spent before evacuation does not allow avoiding the cloud is clearly ineffective, as can be seen in the second case with evacuation radii of 4, 8 and 10 km.

The time spent before evacuation is a very sensitive parameter. For the base case, the times

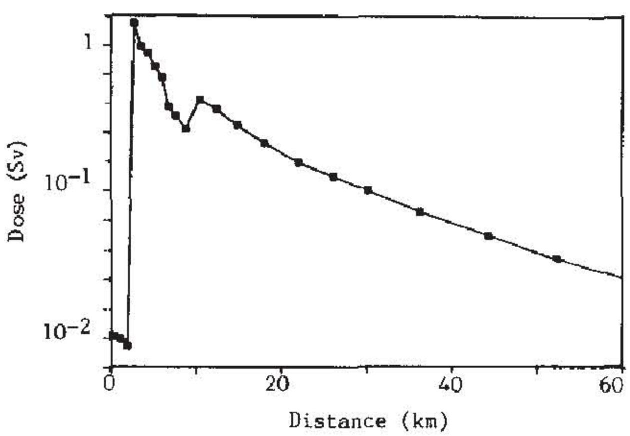

Figure 1. Mean values of centreline acute dose to the bone marrow, as a function of distance, for the base case.

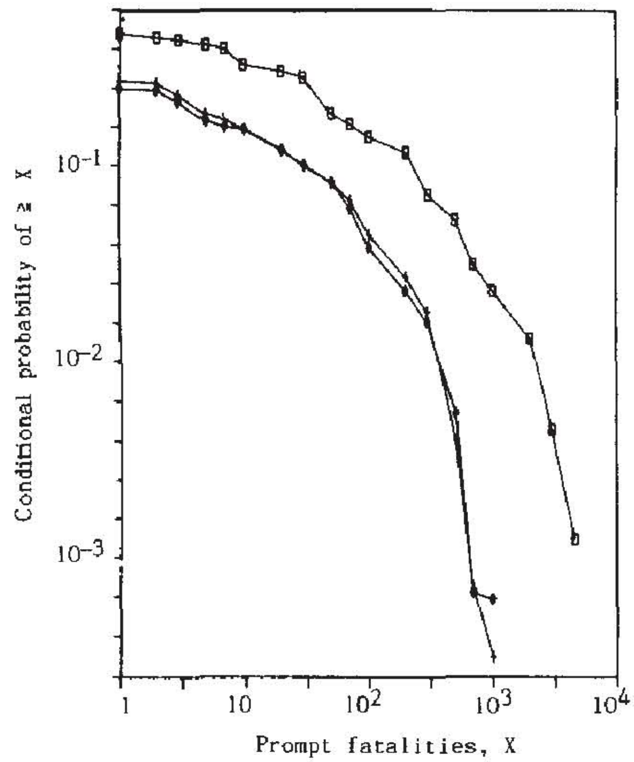

Figure 2. CCDFs for prompt fatalities for different evacuation zones radii: (a) 2-4-6 km (base case); (b) 4-6-8 km; (c) 4-8-10 km. The time spent from scram, before evacuation, is 2, 3 and 4 h for each zone. Key: evacuation to 6 km □; 8 km +; 10 km ◇.

Table 3. Emergency response data for the base case and the alternative cases analysed replacing only one parameter each time. The numbers in parentheses are the mean values of prompt fatalities obtained for each case.

	Base case (103)*	Alternative cases	
Evacuation zones (km)	2-4-6	4-6-8 (18)**	4-8-10 (17)**
Time spent from scram (h)	2-3-4	3-4-4 (261)**	4-4-4 (214)**
Evacuation speed ($m.s^{-1}$)	5.55	8.33 (67)**	11.11 (54)**
Shelter radius (km)	10	16 (99)**	20 (98)**
Relocation dose levels (Sv)	0.1-0.5	0.05-0.25 (100)**	

* Mean value of prompt fatalities obtained for the base case.

** Mean value of prompt fatalities obtained replacing the base case value by the indicated value of each parameter.

measured from the moment of the scram on, inside each of the evacuation zones, were of 2, 3 and 4 h respectively. When the time spent inside the 2 km circle around the reactor inceases up to 3 h, and inside the zone between 2 and 4 km up to 4 h, as the release considered starts 2.5 h after the scram, the plume will catch people before evacuation and the consequences will increase. The mean value of prompt fatalities is 261 for this case, more than double than for the base case. Sometimes, a bad evacuation criterion can lead to an increase of exposure time, if people are evacuated at the same time that the plume is passing over them. This occurs in the previous case. Instead, if evacuation starts once the plume has passed, the consequences will go down. This effect is observed for the 2 km zone, if evacuation also starts 4 h after the scram, reducing the average individual risk of fatality from 0.03 to 0.026, thus giving a mean value of prompt fatalities of 214. CCDFs for the cases analysed are displayed in Figure 3.

Increasing the evacuation speed can reduce the doses received while moving, as the time of contact between the plume and evacuees will be shorter. In fact, an increase in speed from 5.55 $m.s^{-1}$ (20 $km.h^{-1}$) to 8.33 $m.s^{-1}$ (30 $km.h^{-1}$) results in a decrease in the mean value of prompt fatalities from 103 to 67, and

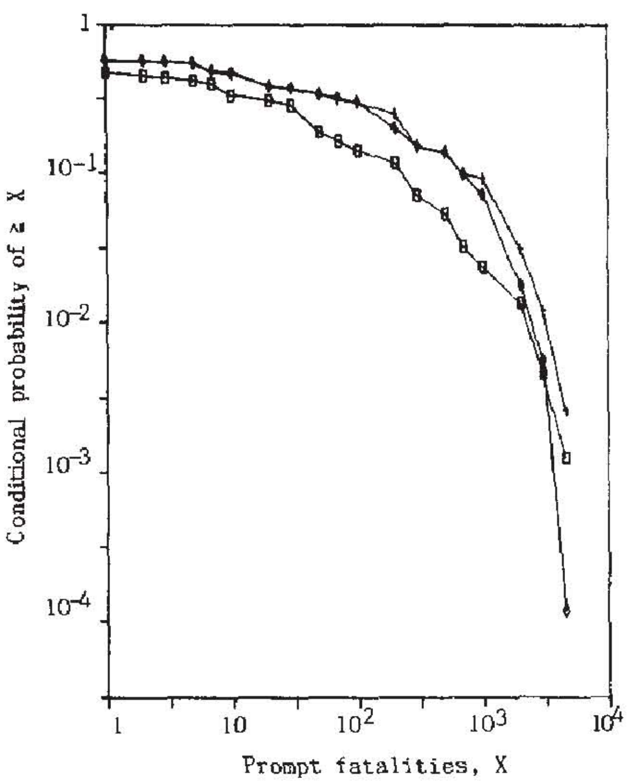

Figure 3. CCDFs for prompt fatalities for different times spent after scram before evacuation inside the 2-4-6 km zones: (a) 2, 3 and 4 h (base case); (b) 3, 4 and 4 h. (c) 4 h for all. Key: 2-3-4 h □; 3-4-4 h +; 4-4-4 h ◇.

a subsequent increase in speed to 11.11 $m.s^{-1}$ (40 $km.h^{-1}$) reduces the mean value to 54 (see Table 3).

The effect produced after enlargement of the sheltering zone is as light reduction of consequences, with the mean value of prompt fatalities going down to 99 cases for a shelter radius of 16 km and to 98 for 20 km. Again, the model is useful to assess the slight effectiveness of a protective action.

As a final consideration in the emergency phase analysis, a change has been introduced in the dose level relocation criterion. The limits for the 24 h groundshine dose to the bone marrow, that are taken as reference, are reduced to one half of those adopted in the base case (see Table 3). The result is not very good, since the mean value of prompt fatalities only goes down to 100 cases, due to the distance at which relocation is applied (outside the 10 km shelter zone), since the doses are low enough to produce no early fatalities.

LONG-TERM COUNTERMEASURES ANALYSIS

The usefulness of ACA models in analysing the potential benefits of various early emergency countermeasures has been demonstrated. A similar application of such models is now presented for the long-term countermeasures, where economic impact is greater, due to the implementation of chronic dose limits that imply relocation by people living in those areas that should be decontaminated or interdicted. A cost-effectiveness analysis of long-term protective actions will consist of evaluating the costs (both radiological and economic) derived from the dose criterion implementation. The need of modelling the relationships between chronic dose, contamination level, affected area, and affected population, makes ACA models an excellent analytical tool for this analysis. However, cost assessment requires realistic data on economic activities inside the affected areas, decontamination efficiencies and required effort, which will be input to the ACA model.

For the case being analysed, different chronic dose criteria are selected. The reference adopted is the groundshine dose to the bone marrow, or the re-suspension dose to the lungs for the 30 years covering the long-term phase. A range of limit values, from 0.05 to 0.5 Sv, has been studied. As a measure of health impact, total cancer deaths have been selected.

With regard to the economic impact of the accident after implementation of each dose limit, a distribution of the mean values of the different items that constitute the total cost is presented in Table 4, including the results obtained for each criterion. Mean values of expected cancer deaths are also shown in Table 4. As can be seen, decontamination and interdiction of urban areas always represent the greater economic impact. As dose criteria become more restrictive, decontamination of areas highly contaminated is more difficult to accomplish and interdiction is imposed, thus increasing their economic importance.

The behaviour of the mean values estimated for total cancer deaths and for total economic costs for each dose limit criterion is illustrated in Figure 4. It is interesting to note that economic damage is more sensitive to the change in dose criteria than health damage.

Cost effectiveness analysis can be performed in terms of costs per averted death[7] for alternative dose limit criteria. In this way, Table 5 has been elaborated. This method allows one to compare the different criteria, searching for the less harmful. Therefore, the selection of a certain dose limit can be made knowing the relative impact of that choice.

FINAL REMARKS

All the results presented up to now are specific to the assumptions and data considered. It is important to remark that results are very sensitive to the accident scenario considered. As a demonstration of that sensitivity, the following modifications to the base case were analysed:

Site modification

Changes in all the site description data have been introduced, taking the population distribution and meteorological data from a Spanish site, low population, as opposed to the NY case previously selected. Economic data remain unchanged, thus

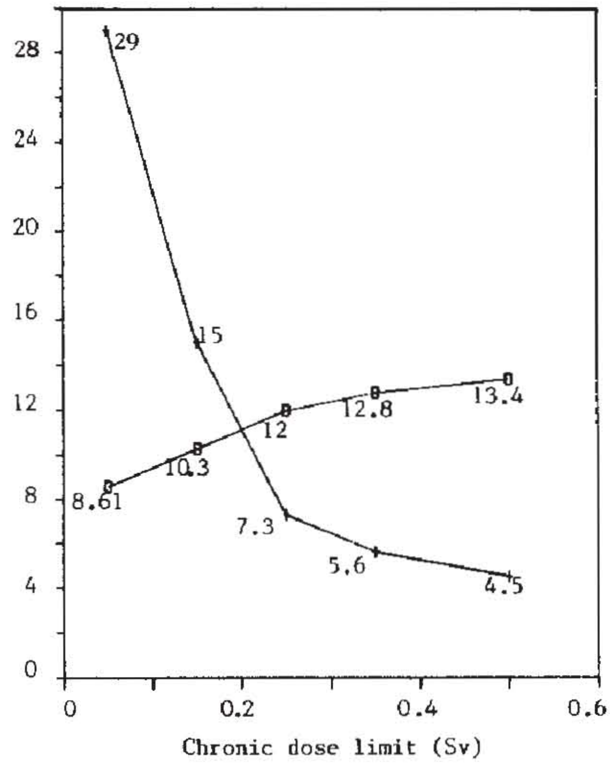

Figure 4. Mean values of total cancer death cases and total economic cost for changes in chronic dose limit. Key: □ cancers × 10^3; + cost in \$ 10^9.

Table 4. Mean values of each economic item and cancer deaths, resulting from implementation of different chronic dose limits.

Chronic dose limit (Sv)	0.05	0.15	0.25	0.35	0.50
Emergency action cost	0.3	0.3	0.3	0.3	0.3
Milk disposal cost	57.5	62.0	62.6	63.0	63.5
Crop disposal cost	27.1	51.1	52.0	52.5	53.3
Urban decontamination cost	1.4×10^4	7.4×10^3	5.5×10^3	4.6×10^3	3.9×10^3
Farmland decontamination cost	2.2×10^2	65.0	31.4	21.1	13.2
Urban interdiction cost	1.5×10^4	6.9×10^3	1.6×10^3	8.4×10^2	3.9×10^2
Farmland interdictions cost	38.9	50.5	50.5	50.7	51.0
Total Economic Cost*	**2.9×10^4**	**1.5×10^4**	**7.3×10^3**	**5.6×10^3**	**4.5×10^3**
Mean cancer deaths**	8.61	10.3	12.0	12.8	13.4

* Costs are expressed in \$$10^6$

** 10^3 cases

Table 5. Cost per averted death for alternative dose limit criteria.

Criteria change (Sv)	Increase in cost (\$)	Decrease in cancer deaths	Cost per averted death (\$)
0.5 -0.35	1.1×10^9	6.0×10^2	1.83×10^6
0.35-0.25	1.7×10^9	8.0×10^2	2.13×10^6
0.25-0.15	7.7×10^9	1.7×10^3	4.53×10^6
0.15-0.05	1.4×10^{10}	1.69×10^3	8.28×10^6

assuming equal unitary costs for protective actions. For early consequences, the predicted mean value of prompt fatalities is only 2, compared with the 103 predicted for the base case; respective CCDFs are shown in Figure 5(a). For latent health effects, the predicted mean value of total cancer deaths drops to 3320, as opposed to the previous 12,000; CCDFs are displayed in Figure 5(b). With regard to economic damage, the mean value of total economic cost is estimated to be $\$1.2\times10^9$, which represents a sixth of the base case value. This drop in economic costs is due to the smaller urban areas considered in the second site.

This simple comparison points towards the necessity of site-specific analysis, since otherwise only general conclusions could be drawn, and no specific application of the analysis could be made.

Source term modification

The source term considered for the base case is a revision of the estimations included in WASH-1400[8]. A more recent analysis[9] of a TMLB'-δ sequence for a PWR shows lower values for the leakage fractions, as well as different temporal evolution of the release. Their main characteristics are detailed in Table 6. With this new source term, including two plume segments, the estimated consequences for the Indian Point site, and the base case assumptions, are much lower. Table 7 contains a summary of them. With exception of some skin injury, no early effects are estimated to occur. This is due to the effectiveness of the emergency plan assumed, since at the start of release, 24 h after initiation of the accident, evacuees are outside the path of the plume. Latent health effects, on the contrary, are still important, with a mean value for total cancer deaths of 2860, which is a fourth of the base case estimation. Finally, the economic impact, in terms of expected total cost, is now of $\$1.4\times10^9$, a fifth of the base case value, the cost of decontaminating urban areas ($\$1.28\times10^9$, 91% of the total, compared with 75% for the base case) prevailing over other costs.

Consequently, source term estimates are very important for cost-effectiveness analysis, as they could change the philosophy of important aspects of emergency planning and long-term protective actions.

SUMMARY AND CONCLUSIONS

A demonstration has been presented on the use of ACA models in cost-effectiveness analysis of countermeasures. Different aspects of emergency planning, such as evacuation time, evacuation speed, sheltering area and early relocation can be analysed with ACA models, evaluating the impact

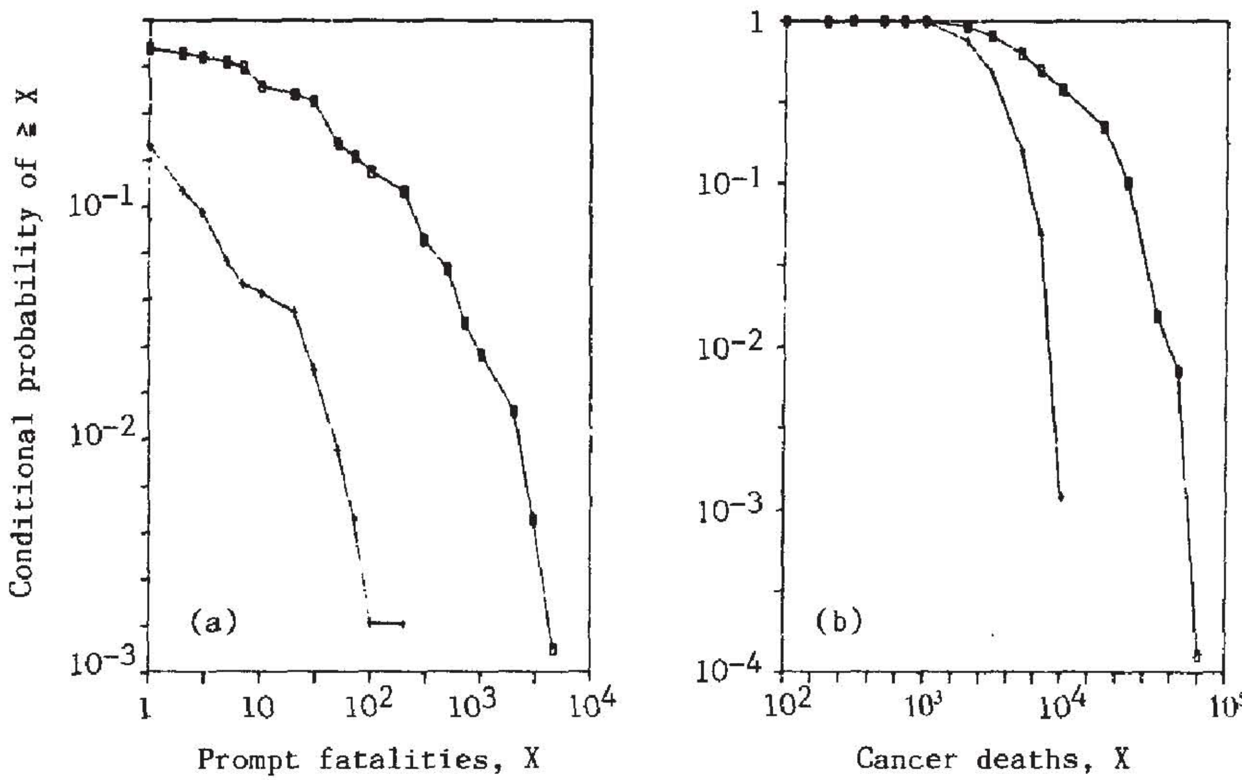

Figure 5. CCDFs for health effects in the two sites analysed: (a) prompt fatalities, (b) total cancer deaths. Key: □ Indian Point; + Spain.

of each assumption on the estimated health damage. Long-term protective actions, including relocation criteria and decontamination, interdicting and food disposal can also be well studied, including interesting relationships between costs and health damages, that could be helpful in decision making. The need of specific analyses for different sources and sites is also emphasised. The results presented are therefore specific to the assumptions and data used, and should not be taken as generic. It is also necessary to remember that important political and social considerations have not been quantified here.

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Table 7. Mean values of consequences estimated with the modified source term, compared with those of the base case.

Type of consequence	Modified source term	Base case
Prompt fatalities	0	103
Cancer deaths	2860	12,000
Urban decontamination cost ($)	1.28×10^7	5.5×10^9
Urban interdiction cost ($)	2.3×10^7	1.6×10^9
Total economic cost ($)	1.4×10^9	7.3×10^9

Table 6. Source term characteristics, for TMLB'-δ PWR accidental sequence (adapted from Blanco[9]).

Accident sequence:	PWR, TMLB'-δ
Number of plume segments:	2
Time of release of each plume segment:	24 h, 24.5 h
Duration of plume segments:	0.5 h, 2 h
Energy of release:	4.44×10^7 W

Fractions of core inventory released

Isotope group	Plume segment 1	Plume segment 2
Xe-Kr	0.65	0.28
I	0.05	0.02
Cs-Rb	2.5×10^{-2}	0.01
Te-Sb	3.5×10^{-6}	1.2×10^{-6}
Ba-Sr	1.5×10^{-2}	4.0×10^{-3}
Ru	1.5×10^{-5}	5.0×10^{-6}
La	1.8×10^{-3}	7.0×10^{-4}

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