
Assessment of the efficiency of short term countermeasures following a severe accident on a PWR

F. Charpin, H. Mansoux, J. Brenot

IPSN, BP n° 6, 92265 Fontenay-aux-Roses, France

Abstract: In case of a severe nuclear accident at a PWR plant, countermeasures will be initiated in the short term by authorities to reduce the consequences of the atmospheric radioactive releases on the neighbouring population. Various factors influence the level of protection afforded by countermeasures. For instance, a too late intervention would lead to a lack of efficiency in terms of dose reduction if the actual evolution of the accident is not considered. Thus, implementation of countermeasures should be optimized. In general, the projected doses (those without countermeasure) are compared with those expected when a particular countermeasure or strategy is implemented. In this paper, an in-depth analysis associates the kinetics of the release with the corresponding evolution of the dosimetric efficiency of countermeasures. This is done at different times in the short term of the accident and for various distances from the plant. Results are presented for different strategies initiated at various times. This work gives useful information for the early management of a major nuclear accident.

1. INTRODUCTION

In case of a severe nuclear accident occurring at a Pressurized Water Reactor (PWR), countermeasures will be initiated in the short term by authorities to reduce the consequences of the atmospheric radioactive releases on the neighbouring population. The calculations presented in this paper aim to assess the efficiency of short term countermeasures and to appreciate their advantages and drawbacks. Parameters and hypotheses required for the dose assessment are presented in section 2. Dose assessment without protective actions and after the implementation of various strategies of countermeasures are presented in section 3.

2. METHODOLOGY

2.1. Accident scenario and releases

The accidental situation considered constitutes the present basis for French emergency plans. This situation covers a set of possible scenarios and is not related to one precise accidental scenario. The initial event is a break of the primary system. The failure of many safety systems, like the emergency core cooling and the containment spray is assumed and leads to a fast core meltdown. The chronology of the associated releases is given in Figure 1.

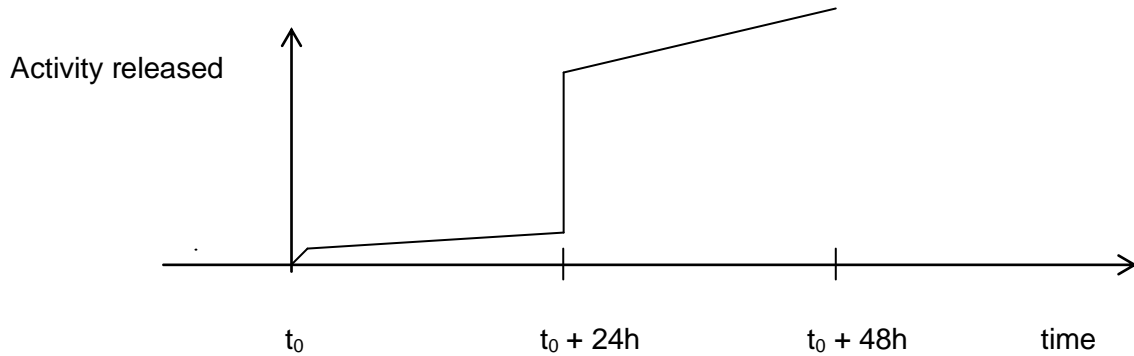


Figure 1: Chronology of the releases

The beginning of the accident is rapidly followed by the alert of the authorities by the operator and by the activation of the emergency plan by the authorities. It is referred as t_0 in Figure 1. The first phase of the release lasts approximately 24 hours. During this period, a limited quantity of radioactivity is released through the normal leaks of the containment. At $t_0 + 24h$, the sand filter is opened to lower the pressure in the containment building and to avoid large uncontrolled releases of radionuclides to the environment. Most of the release occurs during this second phase which also lasts approximately 24 hours.

This release scenario is a reasonable envelope of the releases of various scenarios. Indeed, it is based on pessimistic assumptions. Table 1 presents the total activity released for a 900 MW(e) PWR.

Table 1: Total activity released within 48 hours (900 MW(e) PWR)

Nuclide groups	Noble gases	Iodines	Caesium / Strontium	Tellurium
Total activity released (Bq)	$\sim 5 \cdot 10^{18}$	$\sim 8 \cdot 10^{16}$	$\sim 2.5 \cdot 10^{15}$	$\sim 1.5 \cdot 10^{16}$

2.2. Dispersion and exposure pathways

The study focuses on the short term of the accident, that is the duration of the release, from t_0 to $t_0 + 48h$. The dosimetric consequences of the accident are evaluated for both the adult and the one-year-old child, in the vicinity of the power plant (from 1 to 20 km). Doses are calculated by the SIROCCO code [1], developed by IPSN and based on the Doury atmospheric diffusion model, with the hypothesis of a $5 \text{ m}\cdot\text{s}^{-1}$ wind velocity, normal diffusion conditions and in absence of rainfall. These atmospheric conditions are average conditions for the French nuclear power plants.

During the release, the main exposure pathways are external irradiation by the plume and by the deposits in the environment and internal contamination by the inhaled radionuclides from the plume.

The inhalation dose coefficients come from ICRP publication 71 [2]. Different sets of values are used for the adult and the child. The breathing rates are $22.2 \text{ m}^3/\text{d}$ for the adult and $5.2 \text{ m}^3/\text{d}$ for the child. The dose coefficients for the external irradiation are taken from US Federal Guidance publication 12 [3]. Identical values are used for the adult and the child.

2.3. Projected doses to the public in case of no protective measures

The assessment of the dosimetric consequences of the accident starts with the estimation of the projected individual doses. The projected dose is the dose likely to be received by an individual through all pathways when no protective actions are implemented, the individual of the public being supposed to stay outdoors, under the main direction of the plume during the whole period of the release (48 h).

The protection against radiation brought by buildings is not considered for the dose assessment. This choice is common practice in France. It is conservative and can be seen as a voluntary safety margin of the assessment.

2.4. Short term countermeasures and efficiency

Countermeasures envisaged in the early phase of the accident are sheltering, evacuation of the population and administration of stable iodine. These actions can be combined together. A planned countermeasure is made up of two phases: the notification of the protective action to the public and its implementation. Their durations depend on many factors such as the means used to inform the population, the size of the population of the area, the weather conditions, the moment of the day (working hours, night, and so on).

As long as evacuation is not fully completed, no reduction factor is applied to the doses. When the evacuation is assumed to be completed, no additional exposure is considered.

Sheltering provides a protection against external and internal exposure. For internal exposure, if windows, outer doors and ventilation systems are closed, doses from inhaled radionuclides are reduced but the effectiveness decreases with time. The protection factor for inhalation (PF_{inh}), defined as the ratio between the inhalation dose received indoors and the inhalation dose received outdoors in absence of protection depends on the air exchange rate and on the characteristics of the dwelling. The protection factor is directly multiplied to the projected dose to get the dose after the implementation of the countermeasures. Evaluation of the PF_{inh} was conducted for different kinds of dwellings, with an air exchange rate, λ_e ranging from $0,1 \text{ h}^{-1}$ to 1 h^{-1} . A simple box model relating indoor and outdoor concentrations was used. In this model, the change in indoor air concentration, per unit time is given by the difference between inputs, resuspension from indoor surfaces and losses due to exfiltration, indoor deposition, radioactive decay. Results are presented in table 2.

For external exposure, the protection depends also on the characteristics of the dwelling, in particular the size of the walls, of the roof and the nature of the materials. As for internal exposure, protection factors can be defined. In this study, a constant value was set up for each external pathway, independently of the dwelling characteristics.

Table 2: Protection Factors provided by sheltering

<i>Inhalation Pathway PF_{inh}</i>	24 h	48 h
modern housing (λ_e : 0.1 h^{-1} , statistically 20 to 40 % of the dwellings in France)	0.15	0.39
old but in good state housing (λ_e : 0.3 h^{-1} , statistically 40 to 60 % of the dwellings in France)	0.34	0.60
old and in poor state housing (λ_e : 1 h^{-1} , statistically 20 % of the dwellings in France)	0.62	0.79
PF_{inh} for an average housing (with a weighting of all the dwellings)	0.34	0.57
<i>External Exposure from the plume: PF_{pan}</i>	0.1	
<i>External Exposure from ground deposits: FP_{dep}</i>	0.03	

Provided the building is reasonably air-tight, sheltering can reduce inhalation exposure by a factor of 3 after 24 hours. The reduction factor would be close to 2 after 48 hours because of a gradual ingress of radionuclides into the house. Sheltering can reduce external exposure by at least a factor of 10.

Long term sheltering (more than 48 hours) should not be considered because of the social problems it may induce.

The intake of radioiodine by the thyroid is effectively blocked by oral administration of stable iodine. Stable iodine ingestion protects only the thyroid. It leads to the reduction of the thyroid committed equivalent dose due to inhalation of radioiodine. The evolution of the release (in terms of radioactivity quantity and kinetics) as well as the time of intake of stable iodine compared to the exposure to radioactive iodine influence the efficiency of this protective action. From bibliography [4], we set up the effectiveness in reduction of the thyroid dose from inhalation of radioiodine to 90 % (i.e. a protection factor of 0.1) for the first 24 hours after the intake of stable iodine and to 75 % (i.e. a protection factor of 0.25) for the following 24 hours. A single intake of stable iodine is envisaged here.

2.5. Intervention levels

In France, intervention levels have been set up by the Ministry of Health [5]. They represent the projected dose above which a protective action should be initiated. These intervention levels are guidelines for emergency preparedness. Their use in case of a real accident would be adapted to the specific situation (day-time or night-time, weather conditions, size of the population...). Sheltering is recommended in France when the projected effective dose exceeds 10 mSv, whereas evacuation is recommended when this dose exceeds 50 mSv. The intake of stable iodine is recommended when the thyroid committed equivalent dose by inhalation exceeds 100 mSv for the most sensitive population. These recommended levels are used here.

3. RESULTS

3.1. Projected doses to the public in case of no protective actions

Figure 2 represents the evolution in time of the projected individual effective dose and its breakdown through the internal and external pathways, for an adult at a distance of 5 km from the plant. The large increase of the doses 24 hours after the beginning of the release is due to the opening of the sand filter. Thyroid and effective doses at different times and for various distances are reported in table 3.

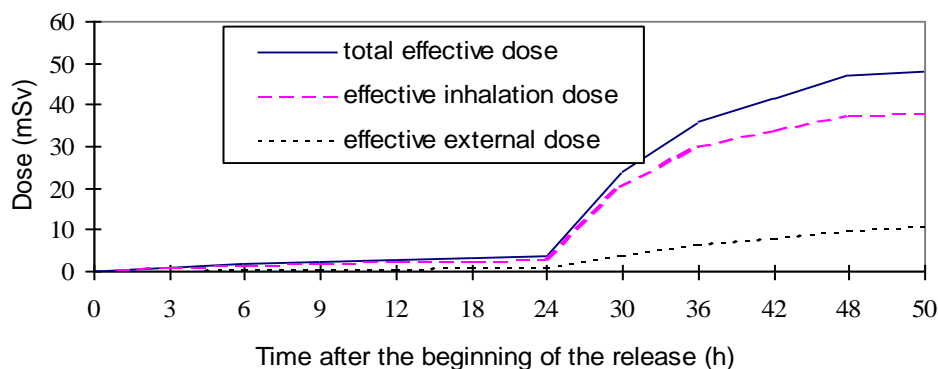


Figure 2: Projected individual effective dose at 5 km from the plant (adult) without any countermeasure

Table 3: Projected individual doses (mSv) without any countermeasure

	Effective dose				Thyroid dose			
	$t_0 + 24h$		$t_0 + 48h$		$t_0 + 24h$		$t_0 + 48h$	
	Adult	One-year-old child	Adult	One-year-old child	Adult	One-year-old child	Adult	One-year-old child
1 km	67.6	84.3	873	1316	382	885	9364	19023
2 km	19.4	24.3	253	382	110	255	2724	5520
3 km	9.2	11.5	120	182	52.2	121	1302	2641
4 km	5.4	6.8	71.1	108	30.7	71.1	771	1561
5 km	3.6	4.5	47.2	71.6	20.3	46.9	514	1041
10	0.98	1.2	13.2	20.1	5.6	12.8	145	293
20	0.27	0.34	3.8	5.8	1.6	3.6	41.8	84.5

Figure 3 and Figure 4 respectively represent the evolution in time of the projected individual effective dose for an adult and the projected individual thyroid dose for a one-year-old child at various distances from the plant. These doses are compared with the intervention levels recommended in France.

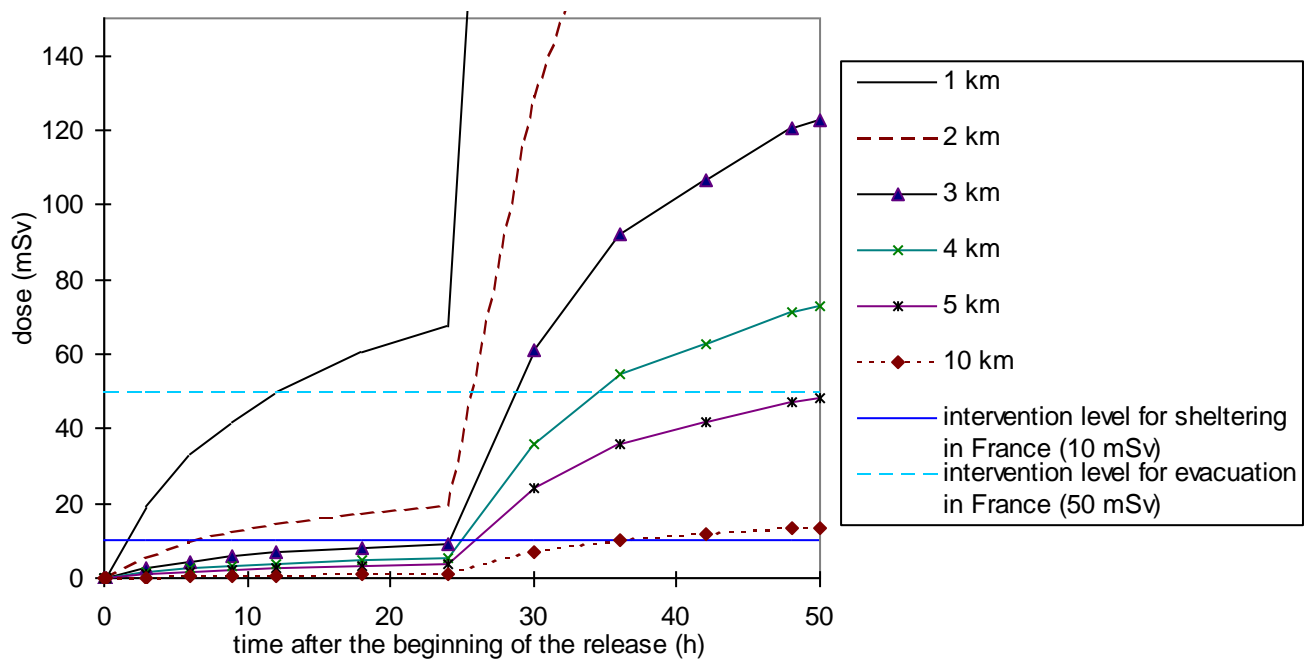


Figure 3: Projected individual effective doses for the adult (mSv)

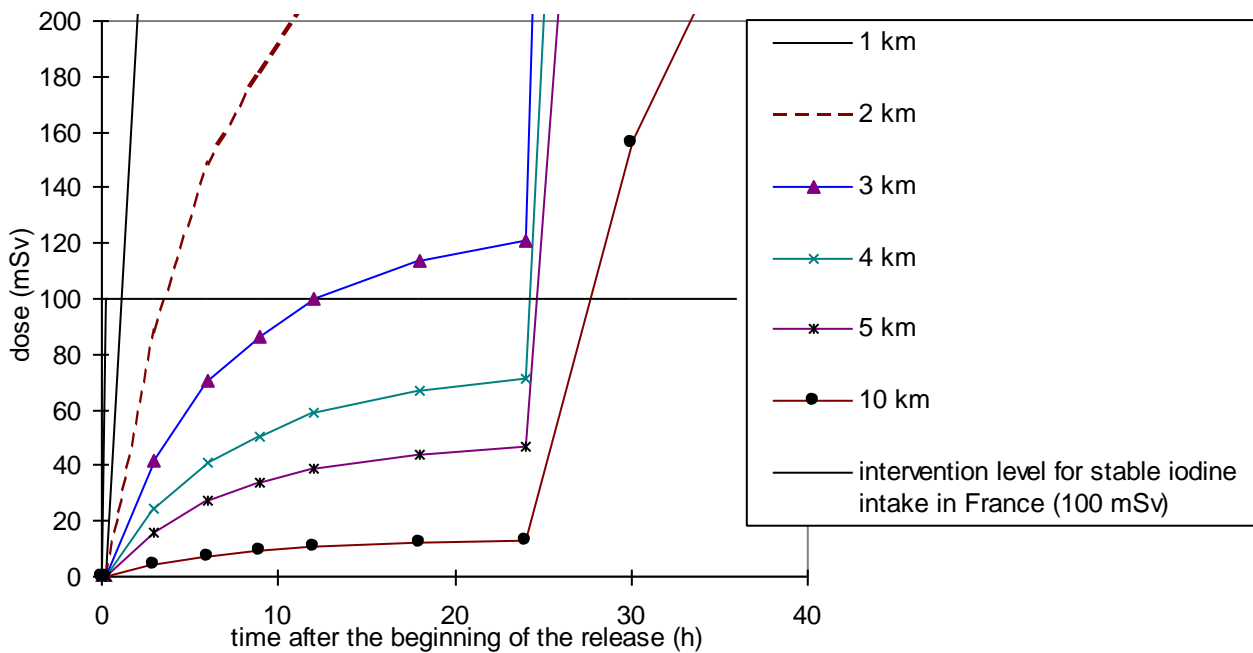


Figure 4: Projected individual thyroid doses for the one-year-old child (mSv)

Assuming that people stand outdoors without protective actions, the 50 mSv evacuation level for the effective dose is exceeded for both the adult and the one-year-old child up to 1-1.5 km, 24 hours after the beginning of the release whereas the 100 mSv level for the thyroid dose is exceeded for the one-year-old child up to 3-4 km. At the end of the release ($t_0 + 48h$), the 50 mSv evacuation level is exceeded over a distance close to 5 km for the adult and over a distance between 6 and 7 km for the one-year-old child. The 100 mSv thyroid dose level is exceeded up to 19 km for the one-year-old child.

3.2. Case study combining sheltering and iodine intake

Two strategies, based on the combination of sheltering and intake of stable iodine are presented. The strategy ST1 assumes that people remain home-sheltered from the beginning of the release till its end and that they take their iodine tablet just before or simultaneously to the first release (at t_0). The strategy ST2 is based on the same hypothesis for the sheltering but stable iodine is taken at $t_0 + 24h$. For strategy ST2, because of the decrease of the stable iodine efficiency, members of the public should be better protected against the major radioiodine release between $t_0 + 24h$ and $t_0 + 48h$.

To compare the evolution in time of the thyroid doses for ST1 or ST2, the dosimetric reduction factor is calculated at each distance from the plant. It is expressed as the ratio of the thyroid dose when the strategy is implemented divided by the projected thyroid dose. The result is independent of the distance. Its evolution with time is presented in Figure 5. Table 4

gives some dose values

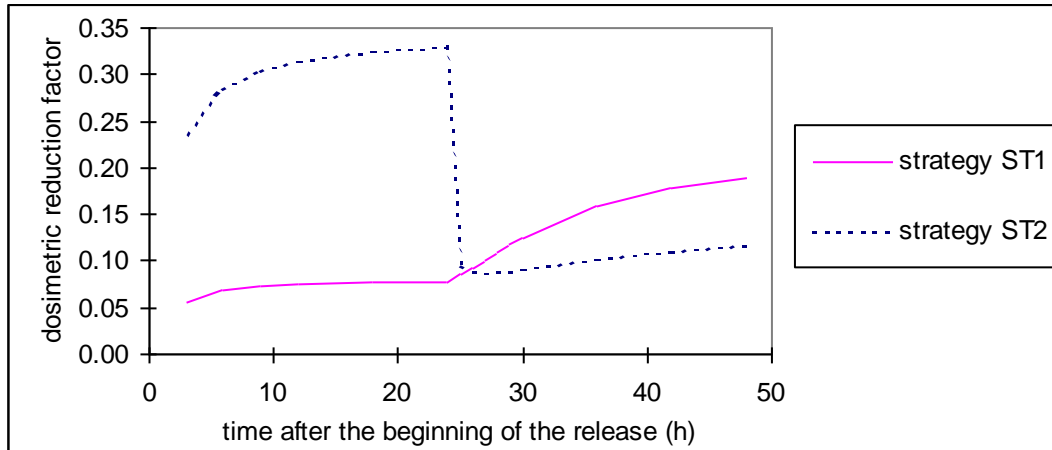


Figure 5: Dosimetric reduction factor (thyroid doses) for strategies ST1 or ST2

The ST1 curve rises slightly with time because of the decrease in sheltering efficiency. The rise of the ST1 curve after 24 hours is also due to the loss of the stable iodine efficiency with time. On the contrary, the strong decrease of the ST2 curve shows the better protection brought by the belated intake of stable iodine.

It can be deduced from Figure 5 that ST1 is more effective -in terms of dose reduction- the first 24 hours. After, ST2 becomes more effective. Twenty four hours after the beginning of the releases, the thyroid dose estimated for ST2 is nearly 4 times higher than the one estimated for ST1, whereas at the end of the release (48 h), the thyroid dose evaluated for ST1 exceeds by a factor 1.6 the dose estimated for ST2. On the overall ST2 appears to be the most protective strategy.

Table 4: Doses (mSv) for ST1 and ST2

Effective dose	$t_0 + 24h$ - ST1		$t_0 + 48h$ - ST1		$t_0 + 24h$ - ST2		$t_0 + 48h$ - ST2	
	Adult	One-year-old child	Adult	One-year-old child	Adult	One-year-old child	Adult	One-year-old child
1 km	12.5	11.6	216	298	17.3	22.6	188	237
2 km	3.6	3.4	62.4	86.6	5	6.5	54.1	68.9
3 km	1.7	1.6	29.6	41	2.4	3.1	25.6	32.5
4 km	1.0	0.9	17.4	24.3	1.4	1.8	15.1	19.3
5 km	0.7	0.6	11.5	16.1	0.9	1.2	10	12.7
10 km	0.2	0.2	3.2	4.5	0.2	0.33	2.8	3.5
20 km	0.05	0.05	0.9	1.3	0.07	0.09	0.8	1
Thyroid dose	$t_0 + 24h$ - ST1		$t_0 + 48h$ - ST1		$t_0 + 24h$ - ST2		$t_0 + 48h$ - ST2	
	Adult	One-year-old child	Adult	One-year-old child	Adult	One-year-old child	Adult	One-year-old child
1 km	29.4	71.5	1771	3572	125	294	1083	2272
2 km	8.5	20.6	515	1036	36.1	84.6	314	657
3 km	4	9.8	246	495	17.1	40.1	149	313
4 km	2.4	5.7	146	292	10.1	23.6	88.3	185
5 km	1.6	3.8	97	195	6.7	15.6	58.7	123
10 km	0.4	1	27.3	54.8	1.8	4.3	16.4	34.2
20 km	0.1	0.3	7.9	15.8	0.5	1.2	4.7	9.8

When ST1 is implemented, the effective dose at 24 hours is found to be inferior to 10 mSv, except on the first km from the plant. At the end of the release (48 hours), despite the protective actions, the effective dose exceeds 50 mSv till 3 km whereas the thyroid dose for the child exceeds 100 mSv on a distance close to 7-8 km.

When ST2 is implemented, the thyroid dose exceeds 100 mSv on the first km between 3 and 6 hours. At the end of the release, the thyroid dose for the child exceeds 100 mSv on a distance close to 5 km.

The results indicate that the protection provided by ST1 and ST2 is not enough for the closest distances (up to 5 km). In order to take the full advantage of the three available countermeasures, a strategy combining evacuation, sheltering and iodine intake is considered below.

3.3. Case study combining evacuation, sheltering and iodine intake

In this case study, countermeasures vary with the distance from the plant. Four geographical zones are defined. Evacuation is now planned in the closest areas. The series of countermeasures envisaged in the ST3 strategy are described precisely before the presentation of the assessed doses. The times presented here for decision-making and implementation of countermeasures by authorities, presently under discussion with the authorities in charge of the public protection, are still theoretical estimates.

In Zone 1 (0 to 2 km around the plant), people are asked to shelter at t_0 . Considering the size of the area, they are expected to be sheltered at home 1 hour after the first alert i.e. at $t_0 + 1h$. Given the evolution of the situation, authorities then ask people to evacuate and to take stable iodine tablets (stable iodine has been distributed in this zone but it can also be

provided during the evacuation). If the order to evacuate is given at $t_0 + 2h$, it is reasonable to think that the area is completely evacuated within two hours, i.e. before $t_0 + 4h$.

In Zone 2 (2 to 5 km around the plant), people are first asked to shelter near $t_0 + 2h$. They are expected to be sheltered at home in less than two hours i.e. before $t_0 + 4h$. At this time, authorities decide to evacuate this zone and also recommend people to take stable iodine tablets (stable iodine has been distributed in this zone but it can also be provided during the evacuation). The evacuation of the downwind sector is expected to last 2 hours so to be completed at around $t_0 + 6h$, whereas the evacuation of the whole circular area would take about 5 hours and would then be completed at $t_0 + 9h$.

In Zone 3 (5 to 10 km around the plant), considering the distance from the plant and the estimated projected doses, the countermeasures considered here are sheltering and intake of stable iodine. At $t_0 + 4h$, authorities start asking people to go home to shelter. People of the downwind sector are expected to be at home at around $t_0 + 11h$. They will be asked to take their iodine tablet soon afterwards and to stay at home till the end of the releases.

Zone 4 (10 to 20 km around the plant): the French emergency plan covers the zones 1, 2 and 3. However in case of an accident which would require sheltering and intake of iodine beyond these zones, provisions would be taken in order to implement those protective actions where they appear necessary. For the accident considered here, these actions would be extended to Zone 4. People would be asked to pick up stable iodine in distribution centres and to go home to shelter. These actions would begin at about $t_0 + 11h$ and would be completed around $t_0 + 19h$. People would then be asked to take stable iodine at around $t_0 + 21h$, before the major part of the release begins.

Table 5 and Table 6 present the doses when ST3 is implemented. In Zones 1 and 2, people are exposed during the evacuation which takes place during the first period of the release. But this exposure ends after respectively $t_0 + 4h$ and $t_0 + 6h$ as a consequence of the evacuation.

Table 5: Doses (mSv) in Zone 1 and Zone 2 for ST3

		Effective dose (mSv)		Thyroid dose (mSv)	
		Adult	One-year-old child	Adult	One-year-old child
ZONE 1 Doses around $t_0 + 4h$	1 km	17	19.4	77.5	185
	2 km	4.9	5.6	22.3	53.4
ZONE 2 Doses around $t_0 + 6h$	4 km	2.5	3	13.8	33
	5 km	1.6	2	9.1	21.8

Table 6: Doses (mSv) in Zone 3 and Zone 4 for ST3.

		Effective dose				Thyroid dose			
		t ₀ + 24h		t ₀ + 48h		t ₀ + 24h		t ₀ + 48h	
		Adult	One-year-old child	Adult	One-year-old child	Adult	One-year-old child	Adult	One-year-old child
ZONE 3	5 km (*)	2.7	3.5	12	14.4	16.5	39	66.9	143
	10 km	0.74	0.93	3.3	4	4.5	10.6	18.7	39.8
ZONE 4	10 km (*)	0.9	1.1	3.4	4	5.3	12.4	17	36.5
	20 km	0.25	0.32	0.95	1.1	1.5	3.5	4.8	10.4

(*): doses may differ at zone limits because the protective actions are implemented at different times in each zone

The thyroid dose in the first km still remains high, despite the fast implementation of the countermeasures in Zone 1. In theory this calls for a faster execution of the countermeasures in this zone. It must be noted however that the accident scenario is based on rather pessimistic assumptions. The maximum effective doses reached in Zones 3 and 4 with ST3 are significantly lowered at 48 hours: 14.4 mSv in Zone 3 and 4 mSv in Zone 4 for the one-year-old child.

4. CONCLUSION

Parameters and hypotheses used for the dose assessment are conservative. They can be discussed, such as the assumptions taken when characterizing the countermeasures and the strategies, which could lead to other calculated doses. Nevertheless, the calculations, as they are, show that substantial dose reductions can be achieved. They provide useful information to judge the efficiency and feasibility of various strategies of countermeasures. In parallel to this theoretical approach, discussion with the authorities in charge of the public protection was initiated to provide practical inputs on both the feasibility of the strategies and the choice of the most appropriate actions.

REFERENCES

1. B. Crabol, M. Monfort, P. Bellier, «Code SIROCCO 2. Manuel de l'utilisateur (version PC)», Note technique SASC 91/841 (1991).
2. International Commission on Radiological Protection, Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 4. Inhalation Dose Coefficients, Publication ICRP 71, Pergamon Press, Oxford (1996).
3. K.F. Eckerman and J.C. Ryman, External Exposure to Radionuclides in Air, Water and Soil, Federal Guidance Report 12- EPA 402-R-93-081 (1993).
4. Ann E. Johnson, The rate of return of radioiodine intake by the normal thyroid after suppression by pharmacological doses of stable iodide, Health Physics, 1963, Vol. 9, pp. 537-538.
5. Niveaux d'intervention DGS/VS5 N°98-018 et 224 (1998).