Feedback on the use of risk metrics for level 2 PSAs

Guillaume Kioseyian [a], Yves Guigueno [a], Emmanuel Raimond [a]
[a] IRSN, BP 17, Fontenay-aux-Roses, 92262, France, *guillaume.kioseyian@irsn.fr*

Abstract: IRSN, acting as the technical and scientific organization in support of the French Nuclear Safety Authority (ASN), has been developing for several years its own Level 2 Probabilistic Safety Assessments (L2 PSAs) for the Nuclear Power Plants (NPPs) operated in France, with significant efforts to have a realistic modelling of the severe accident progression.
The choice of an appropriate set of risk metrics is decisive for understanding and ranking the different severe accident scenarios and to reach a comprehensive understanding of the L2 PSAs results. This paper provides an overview of the risk metrics used at IRSN for L2 PSAs, and gives a feedback on their use.
The set of risk metrics composed of the effective dose, the thyroid equivalent dose and the contamination of soils with caesium-137 is quite useful and satisfactory for presenting the L2 PSAs results. Indeed, this multi-criteria approach provides a very good ranking of the severe accident scenarios by taking into consideration specificities of short- and long-term radiological consequences.
Recently, IRSN has introduced the INES for presenting the IRSN L2 PSAs results in an understandable way. Feedback on the use of the INES is interesting for the communication of results. However, as explained in this paper, some limitations in the assessment of atmospheric release of iodine-131 equivalent, on which the levels of the scale are based, and in the definition itself of the levels have been highlighted. These limitations may yield inappropriate classification of severe accident scenarios resulting from L2 PSAs and lead to think that the INES is not fully adapted to be used as a risk metric for L2 PSAs. Nevertheless, the lessons learned constitute an interesting starting point to define the requirements associated to the development in the future of one risk metric, which could take into consideration both short- and long-term consequences.

Keywords: L2 PSA, risk metric, radiological consequences assessment, multi-criteria approach, INES

1. INTRODUCTION

Level 2 Probabilistic Safety Assessments (L2 PSAs) are an extension of Level 1 Probabilistic Safety Assessments (L1 PSAs). The latter aim at identifying accident sequences leading to core damage and at quantifying their frequency, whereas the objective of L2 PSAs is to assess frequency of releases of radioactive substances in the environment resulting from the progression of such accidents, called severe accidents.

The French Institute for Radiological Protection and Nuclear Safety (IRSN), acting as the technical and scientific organization in support of the French Nuclear Safety Authority (ASN), has been developing for several years its own L2 PSAs for the French Nuclear Power Plants (NPPs), with significant efforts to have a realistic modelling of the severe accident progression. L2 PSAs are used at IRSN for the safety review activities and for internal uses. They are carried out with a set of software tools described in [1], all designed by IRSN engineers and researchers. Thanks to these tools, each L1 PSA accident sequence is extended by severe accident scenarios with an assessment of radioactive releases and radiological consequences.

The choice of an appropriate set of risk metrics is decisive for understanding and ranking the consequences resulting from the severe accident scenarios. This ranking constitutes a key step in identifying the main contributors to the overall risk, and thus in finding out safety improvements.

This paper provides an overview of the risk metrics used at IRSN for L2 PSAs. It describes their advantages and limitations.

2. ASSESSMENT OF RADIOACTIVE RELEASES AND RADIOLOGICAL CONSEQUENCES RESULTING FROM SEVERE ACCIDENT SCENARIOS

For several years, IRSN L2 PSA team has been developing a L2 PSA event tree tool, named KANT [1]. The latter provides functionalities to develop the structure of the Accident Progression Event Tree (APET). The latest improvements of this software in the quantification process, especially the parallelized calculations, allow a more refined assessment of the L2 PSAs results. The number of severe accident scenarios whose radioactive releases and radiological consequences can be assessed is today much more important.

Characterization of radioactive releases and radiological consequences resulting from severe accident scenarios constitutes a key result in the evaluation of risks. A realistic assessment of this data is therefore essential, otherwise accident scenarios with different levels of radioactive releases or radiological consequences would not be properly distinguished and some risks might be overlooked, underestimated or overestimated. A realistic evaluation of radiological consequences needs to take into account, in particular, the chronology (kinetics) and the uncertainties related to the assessment of radioactive releases. To address these points, IRSN L2 PSA team has designed for several years two very fast running codes, named MER and MERCoR. A quick view of these two software is presented below (a more detailed presentation is available in [2]).

2.1 MER software

MER is used to evaluate the amplitude and kinetics of releases for each severe accident scenarios. Only atmospheric radioactive releases are assessed. Radioactive releases in groundwater are presently not considered. All assumptions introduced in MER (fraction of releases for each element from the core, chemistry in the containment, etc.) take into account R&D results on fission products release and behaviour in containment, for instance that of the VERCORS [3], PHEBUS-FP [4] and ISTP [5] programs. Sampling for uncertain parameters (containment break size, mass of released radionuclides from fuel at core meltdown time, etc.) is performed using the Latin Hypercube methodology. The models introduced in MER are sometimes simplified in comparison with those of the ASTEC (Accident Source Term Evaluation Code) code [6], also developed by IRSN. Nevertheless, the consistency of both tools is regularly cross-checked, the ASTEC code being used for the validation of MER [1]. The main difference between MER and ASTEC is that MER does not calculate the severe accident physical phenomena but only the consequences of these phenomena on the radioelement behaviour. Thus, MER provides fast running calculations.

About 250 radionuclides are considered in MER. They are sorted in eight fission products groups: semi-volatile species, volatile species, ruthenium aerosols, halogen aerosols, halogen gases, organic halogen, halogen oxides and noble gases. The first three groups form the aerosol group and halogens (iodine, and bromine to a lesser extent) in their different forms are grouped in the halogen family.

2.2 MERCoR software

To introduce a calculation of radiological consequences in terms of dose or ground deposition, IRSN L2 PSA team has designed the MERCoR software. This tool is based on a database that groups radiological consequences evaluation results for elementary releases. This database is built using the pX and ConsX codes [2], developed by IRSN. MERCoR calculates the radiological impact of releases for a given standard meteorological condition (low diffusion with a wind speed of 2 m/s) and for a 1-year-old child exposed to the radioactive plume in the wind axis (age at which sensitivity to ionizing radiation is the highest for NPPs releases). For each severe accident scenario, consequences can be assessed over the first 90 kilometers from the reactor and the first 30 days after the initiating event. Exposure pathways considered are external exposure from the plume and from ground deposition, and

[1] The ASTEC code is also used to carry out the L2 PSAs support studies, regarding the core degradation for instance.

internal exposure from inhalation (internal exposure from ingestion is not considered but it is planned to address it in the coming years).

Among the 250 radionuclides considered in MER, about 100 are retained in MERCoR. They cover 99% of the radiological consequences.

3. RISK METRICS FOR L2 PSAS

As said in the document published by the ASAMPSA_E project [7], the choice of one appropriate risk metric or a set of risk metrics depends on the decision making approach as well as on the associated goals (risk overall review, identification of plant safety improvements, off-site emergency plant definition, etc.).

3.1 IRSN historical multi-criteria approach with a set of risk metrics

In the first versions of L2 PSAs at IRSN, the presented results were the frequencies of the different containment failure modes and the amplitude of radioactive releases in Becquerel. This presentation was consistent with the definition of a L2 PSA, but it was then difficult to have a good understanding of the issues associated to the severe accident scenarios and to promote the needed safety NPPs reinforcements, in particular at a periodic safety review, using L2 PSAs results. IRSN L2 PSA team therefore decided to assess the radiological consequences, although they are considered to be part of L3 PSA. From that moment, the L2 PSAs developed by IRSN have been considered as "L2+ PSA" [2]. The calculation of radiological consequences was performed with postulated meteorological conditions, and as a function of the distance to the NPP and of the time after the initiating event. Three risk metrics, presented below, were then chosen by IRSN to cover short- and long-term radiological consequences. Moreover, a calculation of a global risk associated to each risk metric was introduced, by multiplying the frequency of a severe accident scenario with the quantified radiological consequences it induces. The contribution of each scenario to a given global risk was then available. This has brought a better understanding of the consequences of a severe accident, especially regarding the distance from NPP where protection measures for population are needed.

Nowadays, this set of risk metrics is still used at IRSN and provides a quite useful and satisfactory multi-criteria approach.

3.1.1 Short-term risk metric

The **effective dose** and the **thyroid equivalent dose** are chosen to assess the short-term radiological consequences because of their use in the French Public Health Code to define the intervention trigger levels in case of radiological emergencies [8]. Table 1 presents the three protection measures and their associated trigger level.

Table 1: French intervention trigger levels in case of radiological emergencies [8]

Protection measure	Indicator	Trigger level (mSv)
Sheltering	Effective dose (all pathways of exposure except ingestion)	10
Evacuation		50
Administration of a stable iodine tablet	Thyroid equivalent dose (all pathways of exposure except ingestion)	50

Using these two indicators, results of necessary time application and geographical extent of each protection measure are assessed with MERCoR for all severe accident scenarios.

The use of the effective dose and the thyroid equivalent dose as short-term risk metrics is highly satisfactory for presenting the L2 PSAs results.

3.1.2 Long-term risk metric

The contamination of soils with caesium-137 is chosen to assess the long-term radiological consequences in order to compare the long-term results of all severe accident scenarios to those of Chernobyl accident. Criteria based on this risk metric were indeed used to define the extent of contaminated territories after the accident in 1986. They are recalled in Table 2.

Table 2: Zoning of territories affected by radioactive contamination resulting from the catastrophe at the Chernobyl NPP [9]

Caesium-137 ground deposition (kBq/m^2)	Zone designation in Russian Federation	Zone designation in Belarus	Zone designation in Ukraine	Zone designation in this paper
37−185	Favourable social and economic status	Periodic control	Reinforced radiological control	Radiological control
185−555	Right of relocation	Right to be resettled	Guaranteed voluntary resettlement	Voluntary resettlement
555−1,480	Relocation	Subsequent relocation	Obligatory resettlement	Subsequent resettlement
> 1,480	Obligatory relocation	Immediate resettlement	Obligatory resettlement	Primary resettlement

As said in paragraph 2.2, the contamination of soils with caesium-137 is assessed with MERCoR for all severe accident scenarios. This is estimated at several distances from the reactor and 15 days after the initiating event of the accident. These long-term consequences are usable for several years, although they are estimated 15 days after the initiating event, because caesium-137 has a half-life of about 30 years. It should be noted that two years after the Fukushima Daiichi accident, caesium-137 already represented 64% of the activity of the residual radioactive deposits [10].

Feedback on the use of this risk metric to compare the long-term results of all severe accident scenarios to those of Chernobyl accident is quite good. Nevertheless, in the event of a nuclear accident, the contamination of soils with caesium-137 would not be used in France to define post-accident zoning. In 2005, the ASN formed a Steering Committee for the Management of the Post-Accident Phase in the Event of Nuclear Accident or a Radiological Emergency Situation (CODIRPA). This committee was in charge of establishing a policy framework to prepare and implement the necessary steps to address post-accident situations following a nuclear accident or a radiological emergency [11]. The guidance values adopted by CODIRPA to establish post-accident zoning is presented in Table 3. They are based on the effective dose, and not on the contamination of soils with caesium-137.

Table 3: French indicators and guidance values for defining post-accident zoning [12] [2]

Zone	Indicator	Guidance value
Heightened territorial surveillance zone (ZST)	Maximum permitted levels of contamination of foodstuffs	According to foodstuffs
Public protection zone (ZPP)	Effective dose (all pathways of exposure)	> 10 mSv during the first month following the end of release
	Thyroid equivalent dose (all pathways of exposure)	> 50 mSv during the first month following the end of release
Relocation perimeter (PE)	Effective dose (all pathways of exposure except ingestion)	> 10 mSv during the first month following the end of release

[2] A revision of the CODIRPA doctrine is in progress.

Finally, it might be useful in the future to complete the current long-term risk metric (the contamination of soils with caesium-137) with the French indicators so as to extend the comparison of long-term results.

3.2 Use of the INES for presenting the L2 PSAs results in a comprehensive way

Recently, IRSN has decided to extend the current set of risk metrics of the L2 PSAs, presented in 3.1, with a communication tool in order to facilitate the understanding of the results towards non-L2 PSAs specialists. To fulfill this goal, IRSN L2 PSA team has chosen the **radiological equivalence to iodine-131 for releases to the atmosphere**. Indeed, this metric is used to define the International Nuclear and radiological Event Scale (INES). The INES was developed in 1990 by the International Atomic Energy Agency (IAEA) to allow prompt communication of the significance of a nuclear event [13]. Events are rated on the INES at seven levels: levels 1 to 3 are called incidents whereas levels 4 to 7 are called accidents. The INES is designed so that the severity of a nuclear event is about ten times greater, in terms of atmospheric release of iodine-131 equivalent, for each increase in level on the scale.

The calculation of radiological equivalence to iodine-131 for releases to the atmosphere is defined by the IAEA [13]. The principle is to calculate and apply multiplying factors to the activity released for a given radionuclide to provide, for this radionuclide, an iodine-131 equivalent activity. About twenty radionuclides are considered in the INES, such as caesium-137, plutonium-239, strontium-90 and obviously iodine-131. To compute these factors, the effective dose to adult is used, and exposure from **inhalation** (short-term aspect) and **ground deposition over 50 years** (long-term aspect) are considered. As the exposure from the plume is not considered, the noble gases are neglected in the INES (their multiplying factor is equal to 0 [3]). IAEA assumptions on the breathing rate[4] and deposition velocities[5] are used in MERCoR evaluations.

As intended, it has been possible to associate an INES level to each severe accident scenario. However some limitations have been found regarding the representativeness of the atmospheric release of iodine-131 equivalent and of the levels themselves for covering both short- and long-term consequences resulting from severe accident scenarios. The following explains what the limitations of the INES are and why the use of this scale for presenting the L2 PSAs results is not always representative of the severity of the accident. To illustrate these two points, results of the French 900 MWe Pressurised Water Reactors (PWRs) internal initiating events L2 PSA study are used. This L2 PSA has generated about 500,000 hypothetical severe accident scenarios that differ in terms of initial plant conditions (power or shutdown states), systems availability, physical parameters such as the containment pressure, containment failure mode and accident kinetics. Those 500,000 scenarios have been grouped at the end of the APET in about 50,000 release categories in which the amplitude and kinetics of releases are supposed to be of the same order of magnitude. Then, radioactive releases and radiological consequences have been assessed for each release category with MER and MERCoR.

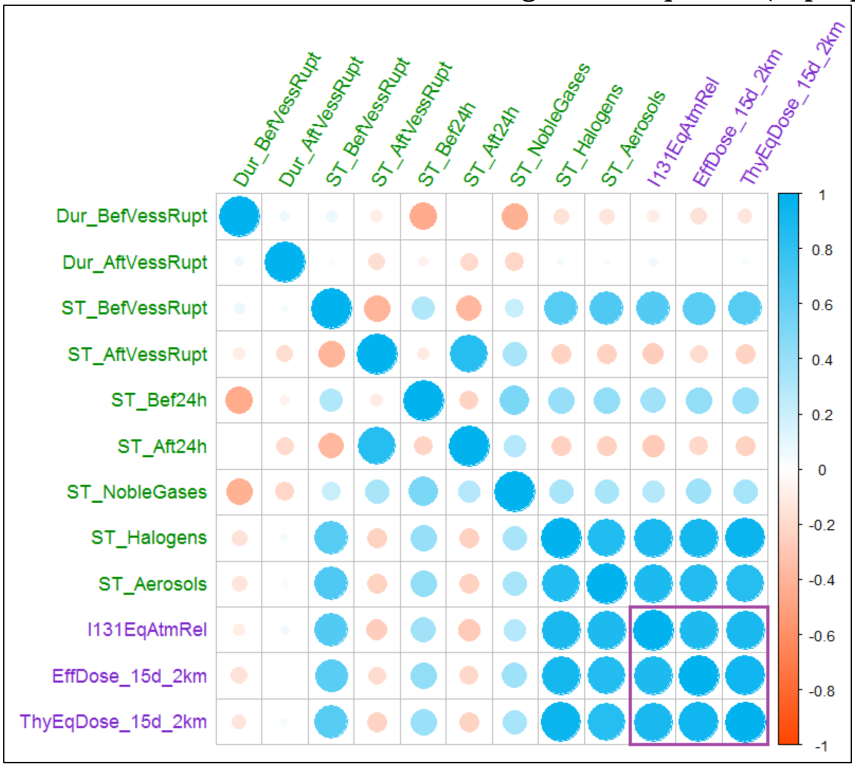
[3] The main exposure due to the noble gases comes from the plume.
[4] 3.3E-04 m^3/s [13].
[5] 1.0E-02 m/s for elemental iodine and 1.5E-03 m/s for other materials [13].

3.2.1 Limitations of using the INES to cover short-term risks

Figure 1 shows correlations between some physical data concerning the radioactive releases (in green) and the risk metrics for the radiological consequences (in purple), except for the soils contamination with caesium-137. This correlogram is obtained by considering the Kendall correlation method [14] that can detect linear or non-linear monotonic relationships. As a reminder, 50,000 couples of data are used to build this correlogram. To interpret Figure 1, the following three points have to be known:

- the larger the disk surface is, the greater the magnitude of the correlation is;
- if the disk color tends toward blue (resp. orange), the correlation is monotonically increasing (resp. decreasing);
- the correlation between two variables X and Y is equal to 1 when Y = X, that is why the magnitudes on the diagonal of the correlogram are equal to 1.

Figure 1: Correlation between physical data concerning radioactive releases (in green) and radiological consequences (in purple)



Legend

Dur_*VessRupt: duration before/after vessel rupture

ST_*VessRupt: source term before/after vessel rupture

ST_*24h: source term before/after 24 hours following the initiating event

ST_NobleGases: source term of noble gases

ST_Halogens: source term of halogens

ST_Aerosols: source term of aerosols

I131EqAtmRel: atmospheric release of iodine-131 equivalent

EffDose_15d_2km: effective dose at 2 km from the reactor 15 days after the initiating event (all pathways of exposure except ingestion)

ThyEqDose_15d_2km: thyroid equivalent dose at 2 km from the reactor 15 days after the initiating event (all pathways of exposure except ingestion)

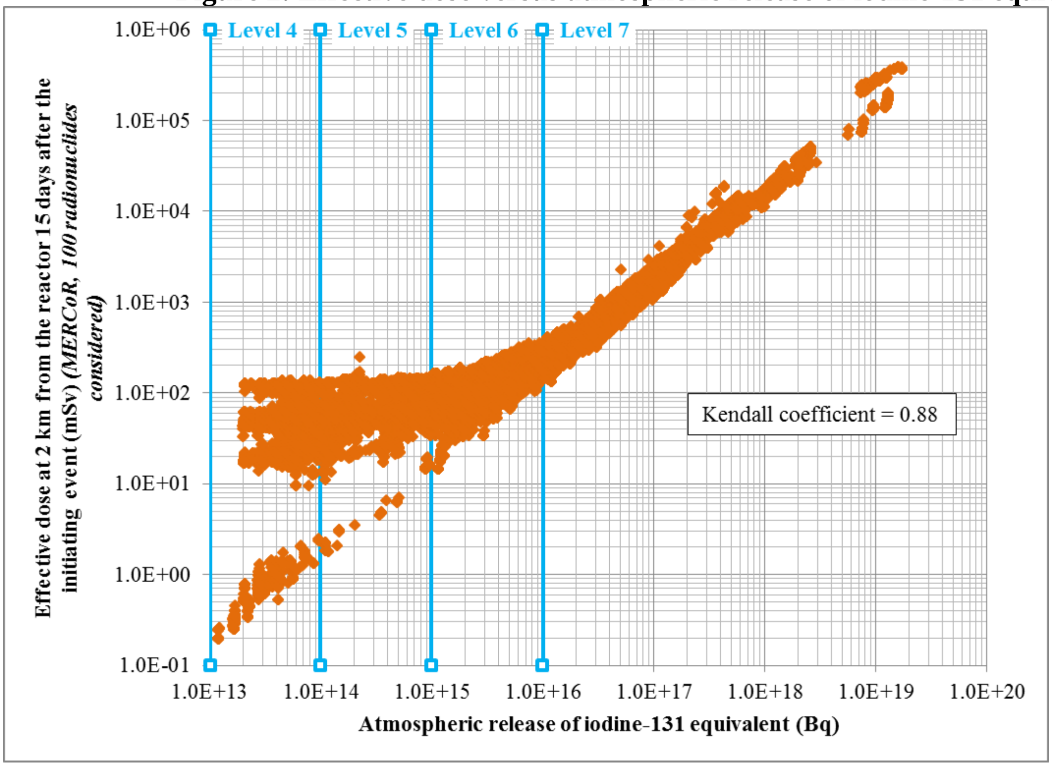
Figure 1 indicates firstly that atmospheric release of iodine-131 equivalent seems to be highly correlated with the short-term risk metrics (effective dose and thyroid equivalent dose). Secondly, the source terms of aerosols and halogens appear to be the main fission product groups that impact radiological consequences.

Figure 2 shows the effective dose versus the atmospheric release of iodine-131 equivalent. In this graph, each orange dot corresponds to a release category (there are therefore about 50,000 dots). As seen in Figure 1, Figure 2 confirms the important correlation between the effective dose and the atmospheric release of iodine-131 equivalent. However, two limitations appear in the use of the radiological equivalence to iodine-131 for releases to the atmosphere, and therefore of the INES, for presenting the L2 PSAs results, as discussed in the following.

Firstly, some INES levels group a very large set of severe accident scenarios whose short-term consequences are very different. Indeed, level 4 extends from about 2.0E-01 mSv (at 2 km from the reactor 15 days after the initiating event) to about 1.0E+02 mSv, and level 7 extends from about 1.0E+02 mSv to about 1.0E+05 mSv. Scenarios rated level 7 are studied as a priority so as to decrease the overall risk. On an indicative basis, for the IRSN 900 MWe PWRs internal initiating events L2 PSA study, about 85% of the core damage frequency leads to an atmospheric release of iodine-131 equivalent lower than 1.0E+17 Bq. It should be noted that this study does not consider the post-Fukushima Daiichi complementary safety assessments and related plant modifications.

Secondly, below an atmospheric release of iodine-131 equivalent of 2.0E+15 Bq, the correlation is not so clear, and the use of this metric may introduce inversions in the short-term risk assessment. Indeed, the severity induced by severe accident scenarios is supposed to increase with the level on the scale, but Figure 2 points out that some release categories rated level 4 on the INES induce an effective dose of about 1.0E+02 mSv (at 2 km from the reactor 15 days after the initiating event) whereas others rated level 5 lead to a dose of about 2.0E+00 mSv. Moreover, some release categories rated level 4 on the INES induce an effective dose as significant as some release categories rated level 7.

Figure 2: Effective dose versus atmospheric release of iodine-131 equivalent



Legend

Level 4: level 4 on the INES - Accident with local consequences

Level 5: level 5 on the INES - Accident with wider consequences

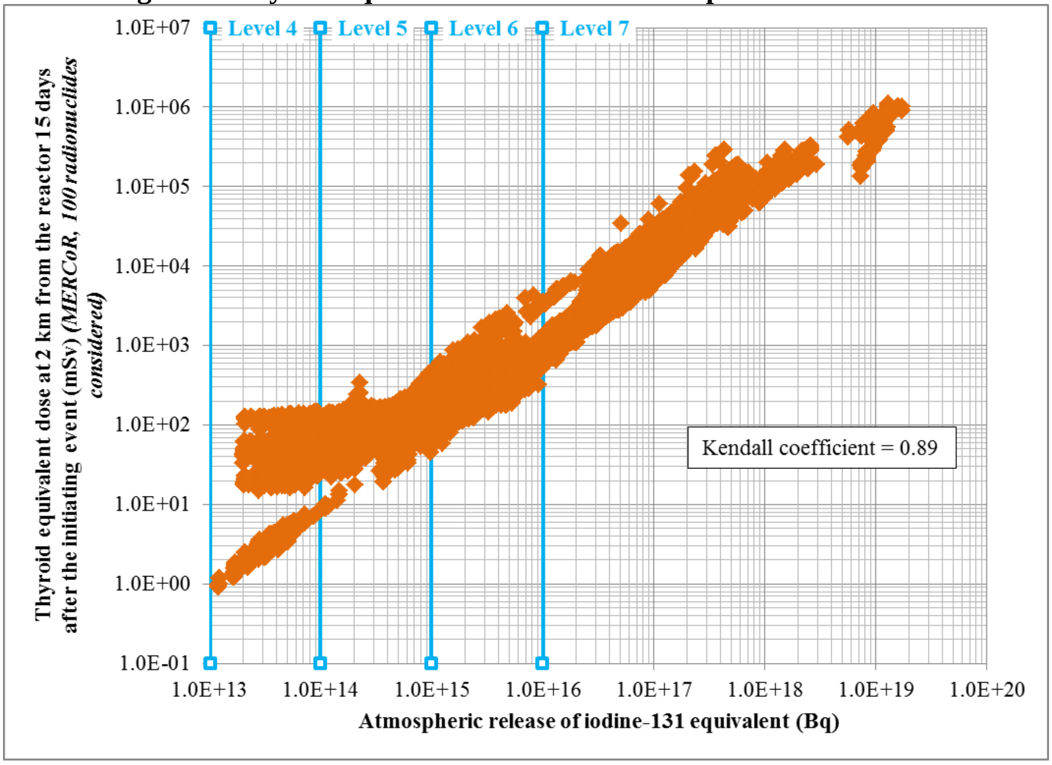
Level 6: level 6 on the INES - Serious accident

Level 7: level 7 on the INES - Major accident

Conclusions from Figure 2 are also observable when plotting the thyroid equivalent dose versus the atmospheric release of iodine-131 equivalent (cf. Figure 3). Nevertheless, the separation between these two risk metrics (below 2.0E+15 Bq of atmospheric release of iodine-131 equivalent) is less visible than in Figure 2.

Besides, Figure 4 points out that the atmospheric release of iodine-131 equivalent and the global source term of aerosols and halogens are highly correlated. Indeed, the graph is almost an identity line ($y = x$ line), as the noble gases are not considered in the calculation of atmospheric release of iodine−131 equivalent.

Figure 3: Thyroid equivalent dose versus atmospheric release of iodine-131 equivalent



Legend

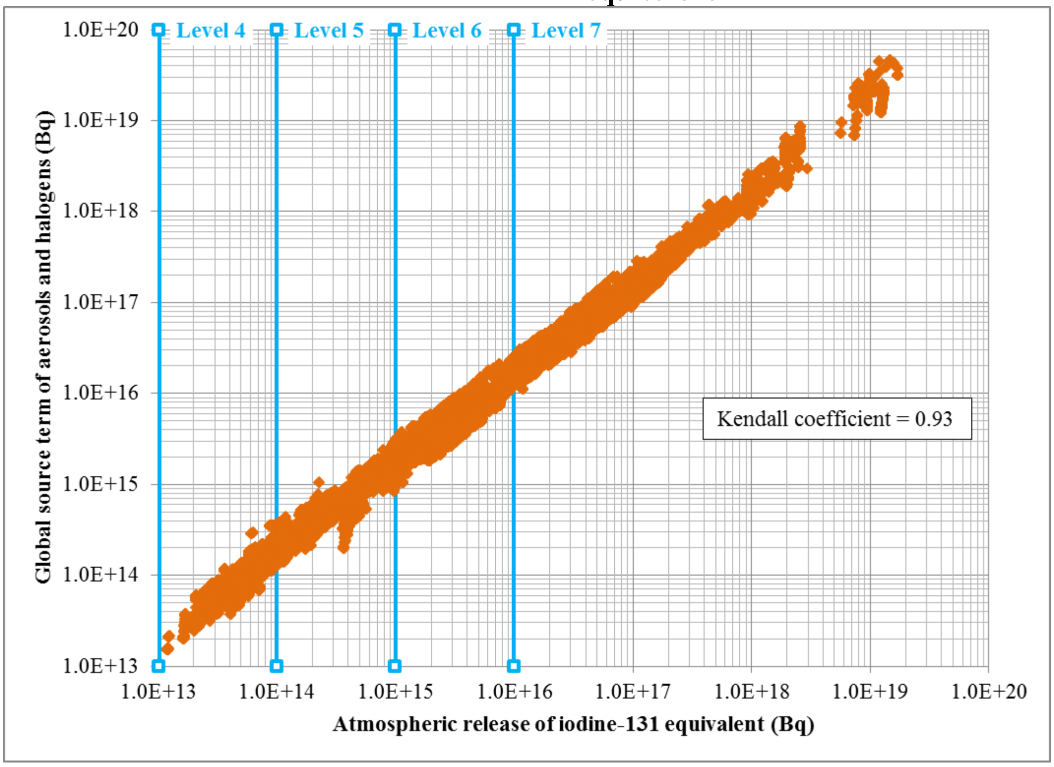
Level 4: level 4 on the INES - Accident with local consequences

Level 5: level 5 on the INES - Accident with wider consequences

Level 6: level 6 on the INES - Serious accident

Level 7: level 7 on the INES - Major accident

Figure 4: Global source term of aerosols and halogens versus atmospheric release of iodine-131 equivalent



Legend

Level 4: level 4 on the INES - Accident with local consequences

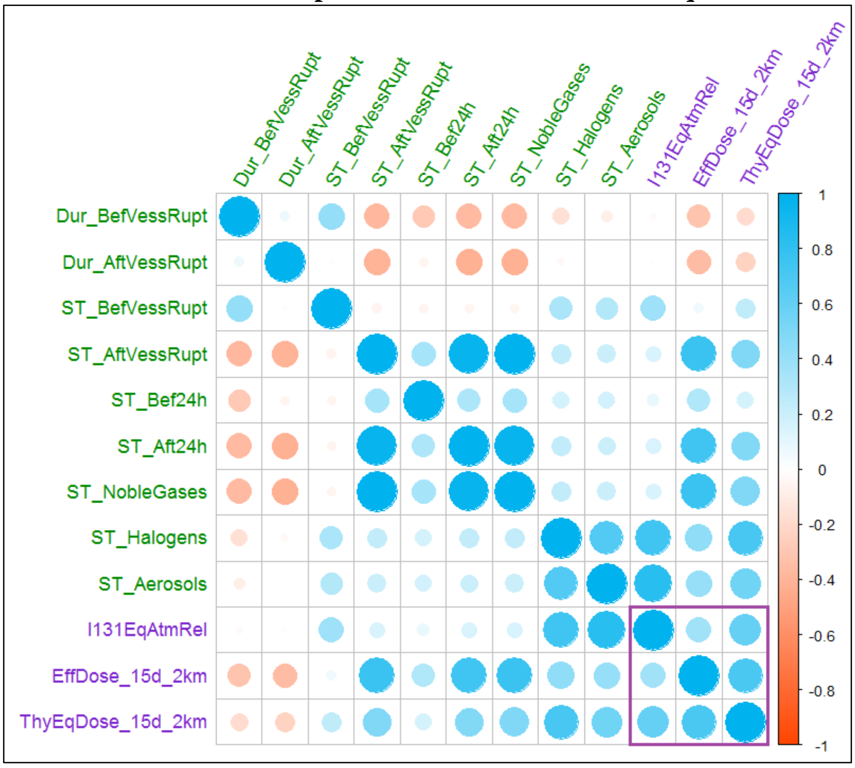
Level 5: level 5 on the INES - Accident with wider consequences

Level 6: level 6 on the INES - Serious accident

Level 7: level 7 on the INES - Major accident

Figure 5 updates the correlations of Figure 1 by considering only the couples of data with an atmospheric release of iodine-131 equivalent lower than 2.0E+15 Bq. As seen in Figure 2, atmospheric release of iodine-131 equivalent is not so well correlated with doses below a value of 2.0E+15 Bq. Moreover, the noble gases source term seems to be the key fission product group regarding the effective dose. Concerning the thyroid equivalent dose, the halogens source term appears the most important fission product group because of the iodine, and the noble gases seems to be as important as aerosols.

Figure 5: Correlation between physical data concerning accident consequences for an atmospheric release of iodine-131 equivalent lower than 2.0E+15 Bq



<u>Legend</u>

Dur_*VessRupt: duration before/after vessel rupture

ST_*VessRupt: source term before/after vessel rupture

ST_*24h: source term before/after 24 hours following the initiating event

ST_NobleGases: source term of noble gases

ST_Halogens: source term of halogens

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I131EqAtmRel: atmospheric release of iodine-131 equivalent

EffDose_15d_2km: effective dose at 2 km from the reactor 15 days after the initiating event (all pathways of exposure except ingestion)

ThyEqDose_15d_2km: thyroid equivalent dose at 2 km from the reactor 15 days after the initiating event (all pathways of exposure except ingestion)

Figure 6 *(a)* is the same as Figure 2 by keeping only data with an atmospheric release of iodine-131 equivalent lower than 2.0E+15 Bq. Figure 6 *(b)* shows the effective dose versus the source term of noble gases, keeping only the severe accident scenarios with an atmospheric release of iodine-131 equivalent lower than 2.0E+15 Bq. The colour of the dots corresponds in Figure 6 *(a)* and *(b)*. The dots in purple (resp. in green) in Figure 6 *(a)* are those for which the source term of noble gases is greater (resp. lower) than 1.0E+17 Bq in Figure 6 *(b)*.

Besides, Figure 7 presents the respective average contribution of aerosols, halogens and noble gases to the effective dose evaluation. For the dots in purple in Figure 6, the contribution of the effective dose from noble gases to the global effective dose is about 90%.

In conclusion, Figure 6 and Figure 7 confirm the importance of noble gases when the atmospheric release of iodine-131 equivalent is below 2.0E+15 Bq and when the source term of noble gases is greater than 1.0E+17 Bq. This situation is mainly encountered in case of a filtered containment venting system opening or in case of a base-mat melt-through failure. Indeed, in these cases, the filtration of aerosols and some halogen forms (in particular halogen aerosols) is significant whereas the noble gases are not filtered. Yet, the assessment of atmospheric release of iodine-131 equivalent based on the INES conversion factors neglects the noble gases. Thus, the use of the radiological equivalence to iodine-131 for releases to the atmosphere, and therefore of the INES, appears inappropriate for these cases and is not relevant for the whole spectrum of severe accidents generated by L2 PSAs.

Figure 6: Effective dose versus *(a)* atmospheric release of iodine-131 equivalent and *(b)* noble gases source term, for an atmospheric release of iodine-131 equivalent lower than 2.0E+15 Bq (the colour of the dots corresponds in *(a)* and *(b)*)

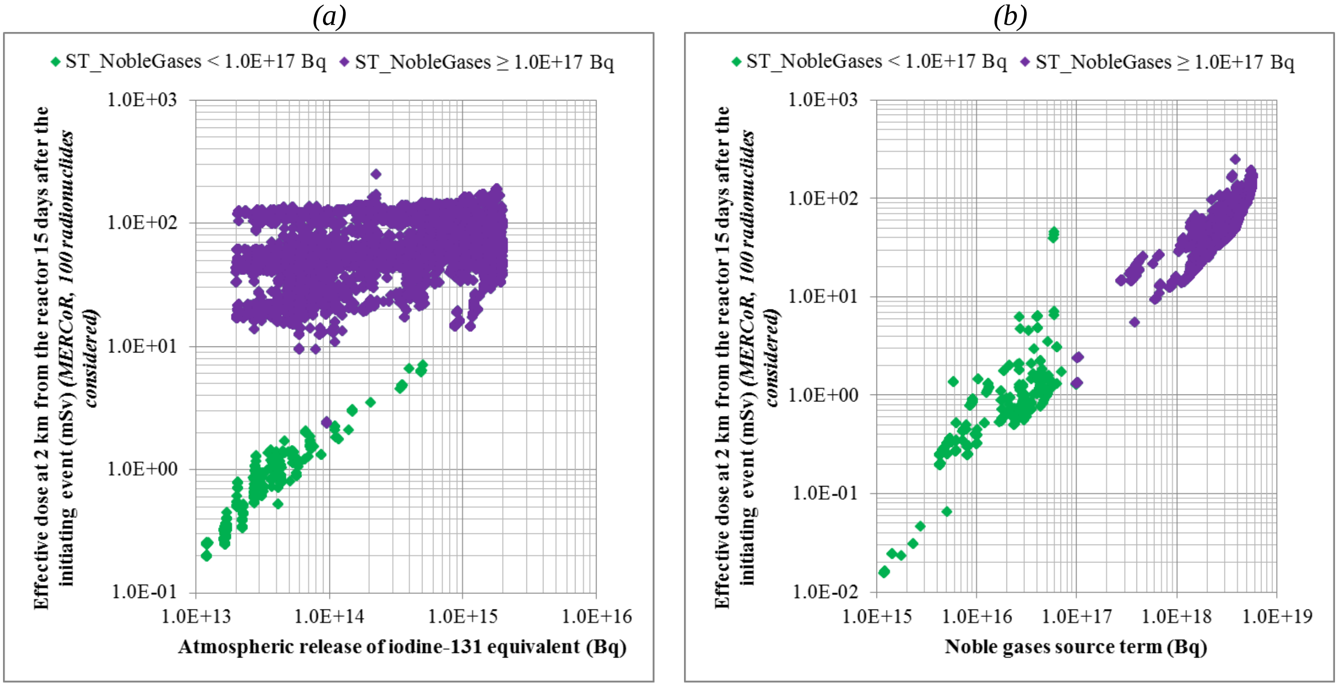
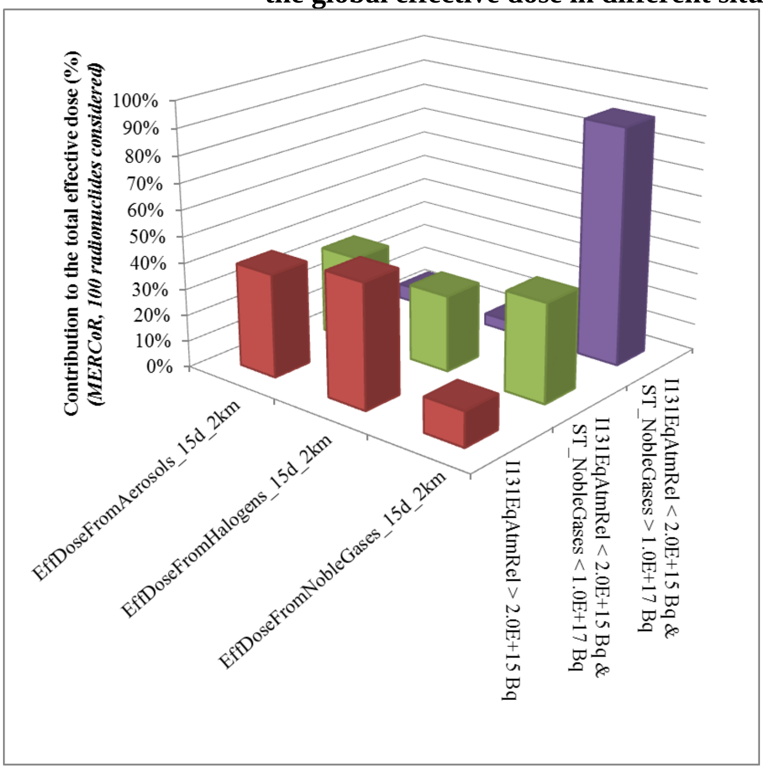


Figure 7: Average contribution of the effective dose from aerosols, halogens and noble gases to the global effective dose in different situations



Legend

*EffDoseFrom*_15d_2km*: effective dose from * at 2 km from the reactor 15 days after the initiating event (all pathways of exposure except ingestion)

I131EqAtmRel: atmospheric release of iodine-131 equivalent

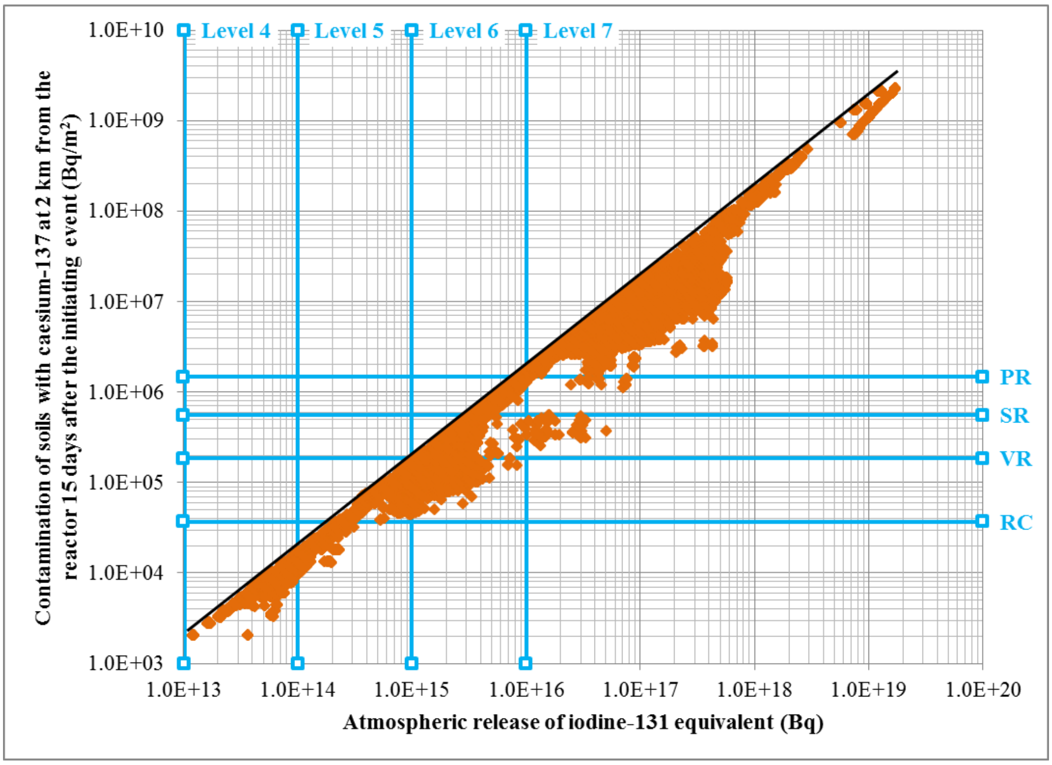
ST_NobleGases: source term of noble gases

3.2.2 Limitations of using the INES to cover long-term risks

Comparison with the current IRSN long-term risk metric

Figure 8 shows the contamination of soils with caesium-137 versus the atmospheric release of iodine-131 equivalent. The correlation between these two data appears high. Some release categories deviate logically to the right from the straight line in black because the INES considers several radionuclides whereas the contamination of soils with caesium-137 take into account only caesium-137. Nevertheless, it should be noted that the application of the INES to the zoning of contaminated territories put in place after the Chernobyl accident may introduce inversions in the risk assessment. Firstly, long-term consequences resulting from severe accident scenarios rated level 7 on the INES span a wide range. Indeed, the zoning of the area extending to 2 km from the reactor varies from "voluntary resettlement" to "primary resettlement". Secondly, some release categories rated level 6 on the INES lead to a more restrictive zoning than others rated level 7.

Figure 8: Contamination of soils with caesium-137 versus atmospheric release of iodine-131 equivalent



Legend

Level 4: level 4 on the INES - Accident with local consequences

Level 5: level 5 on the INES - Accident with wider consequences

Level 6: level 6 on the INES - Serious accident

Level 7: level 7 on the INES - Major accident

RC: Radiological control

VR: Voluntary resettlement

SR: Subsequent resettlement

PR: Primary resettlement

Forecasting comparison with the future IRSN long-term risk metric

As said in paragraph 3.1.2, the French approach for defining post-accident zoning uses the effective dose with all pathways of exposure as indicator, including ingestion. The latter will be integrated in MERCoR in the near future. Thanks to this, IRSN will introduce the French approach in L2 PSAs as a new long-term risk metric. Thus, for each severe accident scenario resulting from L2 PSAs, the necessary extent of the public protection zone and of the relocation perimeter will be assessed.

For some severe accident scenarios, the effective dose resulting from the ingestion exposure may represent up to 75% of the global effective dose, 1 month after the end of release [15]. As the atmospheric release of iodine-131 equivalent does not consider this contribution, the use of the INES to address long-term risks associated to the French post-accident zoning approach seems irrelevant.

4. CONCLUSION

The set of risk metrics composed of the effective dose, the thyroid equivalent dose and the contamination of soils with caesium-137 is quite useful and satisfactory for presenting the L2 PSAs results. Indeed, this multi-criteria approach provides a very good solution to understand and rank the severe accident scenarios by taking into consideration specificities of short- and long-term radiological consequences. Recently, IRSN has introduced the INES as a communication tool for presenting L2 PSAs results in a comprehensive way to non-L2 PSAs specialists. To that end, feedback on the use of the INES is interesting as each severe accident scenario resulting from L2 PSAs can be associated to an INES level. However some limitations of the atmospheric release of iodine-131 equivalent criteria, on which the levels of the scale are based, have been highlighted. These limitations are due to the neglect of the noble gases contribution and, to a lesser extent, that of the exposure from ingestion. Moreover, accidents classified at level 7 can widely differ in terms of radiological consequences. These limitations may yield inappropriate classification of severe accident scenarios resulting from L2 PSAs. This shows that the atmospheric release of iodine-131 equivalent, and so the INES, are not fully adapted to be used as a risk metric for L2 PSAs. Nevertheless, it constitutes an interesting starting point to define the requirements associated to the development in the future of one risk metric, which could take into consideration both short- and long-term consequences.

For the future, IRSN intends to maintain a multi-criteria approach for presenting its L2 PSAs results. IRSN also intends to extend this set with the introduction of indicators and guidance values used for the French post-accident zoning. Regarding the use of one risk metric for presenting the L2 PSAs results, IRSN thinks it could be interesting to combine short- and long-term consequences through the economic cost they may cause. This approach, although quite complex since many parameters have to be taken into consideration, would provide interesting additional information.

References

[1] Y. Guigueno *et al.*, "*Severe accident risk assessment for NPPs - Software tools and methodologies for level 2 PSA development available at IRSN*", PSAM 13, 2016.

[2] T. Durin *et al.*, "*Very fast running codes for the characterization of severe accident radiological consequences and the results presentation in level 2 PSA*", PSAM 11, 2012.

[3] Y. Pontillon *et al.*, "*Behaviour of fission products under severe accident conditions: The VERCORS experimental programme*", Nuclear Engineering and Design, Vol. 240, pp. 1843-1852, 2010.

[4] "*Special Issue: Phebus FP Final Seminar*", Annals of Nuclear Energy, Vol. 61, pp. 1-230, 2013.

[5] B. Clément and R. Zeyen, "*The Phebus Fission Product and Source Term International Programme*", International Conference Nuclear Energy for New Europe, Bled, Slovenia, 2005.

[6] P. Chatelard *et al.*, "*Main modelling features of the ASTEC V2.1 Major Version*", Annals of Nuclear Energy, Vol. 93, pp. 83-93, 2016.

[7] "*Risk Metrics and Measures for an Extended PSA*", European ASAMPSA_E project, Technical report ASAMPSA_E/WP30/D30.7/2017-31 volume 3, ASAMPSA_E website.

[8] "*ASN statutory resolution 2009-DC-0153 of 18th August 2009*", ASN, 2009, ASN website.

[9] "*Present and future environmental impact of the Chernobyl accident*", IPSN, IAEA-TECDOC-1240, available on the IAEA website.

[10] "*Fukushima Daiichi accident - Information note concerning the evolution of the environmental contamination and the contamination of foodstuffs produced in Japan*", IRSN, 2013, IRSN website.

[11] F. Gallay *et al.*, "*French policy for managing the post-accident phase of a nuclear accident*", ICRP, 2013.

[12] "*Policy elements for post-accident management in the event of nuclear accident*", ASN, 2012.

[13] "*INES - The International Nuclear and Radiological Event Scale - User's Manual - 2008 Edition*", IAEA, 2013.

[14] A.I. McLeod, "*Kendall rank correlation and Mann-Kendall trend test*", R Package, 2011.

[15] D. Didier, "*Principaux enjeux de radioprotection en cas d'accident nucléaire*", IRSN presentation, 2014, ANCCLI website.