Experience feedback from Fukushima towards Human Reliability Analysis for level 2 Probabilistic Safety Assessments

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Abstract: In the years 2000, the IRSN developed its first level 2 Probabilistic Safety Assessment (PSA) for the 900 MWe French PWRs. It was an ambitious project and one of the important tasks was to build a Human Reliability Analysis (HRA) model able to model the human actions to be implemented after the core melted. These actions are performed by operators in the main control room or by field operators outside but most of the decisions are taken, on the basis of the Severe Accident Management Guide (SAMG), by the crisis organization.
A Human and Organizational Reliability Analysis in Accident Management (HORAAM) model is born from this enterprise. It is based on the "Decision Tree method". HORAAM has been developed from the observation of the nuclear crisis exercises that are regularly practiced in France. Several influence factors which particularly affect human and organizational reliability in such a situation were identified.
Currently HORAAM is used at IRSN but it has never been compared to the experience feedback of a real accident. After the Fukushima accident, IRSN conducted a study to confront HORAAM with the difficulties encountered to implement actions after the core meltdown. The purpose of this article is to present the main conclusions drawn from this study.

Keywords: PSA / HRA / FUKUSHIMA / SAMG / NUCLEAR CRISIS

1. INTRODUCTION

In the years 2000, IRSN developed its first level 2 Probabilistic Safety Assessment (PSA) model for the French 900 MWe PWRs. It was an ambitious project and one of the important tasks was to build a Human Reliability Analysis (HRA) model for the actions of the Severe Accident Management Guide (SAMG). Human and Organizational Reliability Analysis in Accident Management (HORAAM) model was developed for this purpose.
On the damaged unit, after the core melted, actions are implemented by the crew but they result from decisions that may be taken by the nuclear crisis organisation. The experience feedback from operators applying Emergency Operating Procedures (EOPs) on simulators, widely used for level 1 HRA models, couldn't be reused to design HORAAM. First indeed, actions are oriented to the single goal of reducing the release consequences but the level 2 HRA model had also to include the information exchange and the decision processes which are crucial mechanisms for the crisis center activities in such a context. To validate their assumptions, the HORAAM developers have used feedback analyses of the nuclear crisis exercises that are regularly practiced in France.
HORAAM has then been used at IRSN to produce HRA data for level 2 PSAs for the French PWRs but was of course never compared with a real accident. In 2012, IRSN conducted a study to confront HORAAM with difficulties encountered during the Fukushima-Daiichi accidents to implement actions after the core meltdown. This paper presents the main conclusions of this study.

2. PRESENTATION OF HORAAM

2.1. The decision tree method

HORAAM is a “decision tree (DT) model”. The DT methodology relies on the hypothesis that the failure probability of a human action can be evaluated through a limited number of factors. These factors are called “Influence Factors” (IFs) and they illustrate the context of a human action. They are chosen in order to take into account in the best possible way the factors that have an effect on the implementation of the action and particularly the related difficulties: IFs must be indeed numerous enough to take into account the main aspects of the action but not too numerous in order to limit the complexity of the event tree. A theoretical example of a DT is presented on Table 1 below. Its goal is to evaluate the failure probability of an action implemented in the main control room to cope with an initiating event through four IFs.
The IFs are ranked from the most influent to the less influent. The number of modalities (or branches) is adjusted to reflect the relative influence of the IFs. If possible, IFs take only two modalities to limit the complexity of the model. Next step once the structure of the DT is finalized is to quantify the probabilities associated to each branch of the tree. Several quantification technics can be used but all are a combination of “anchor probabilities” (statistics from observation for few branches) and “partial probabilities” (expert judgment).
Thus the individual effect of each IF is integrated to yield the corresponding probabilities and to account for dependencies between IFs. Different combinations of IFs can lead to greatly different Human Error Probabilities (HEPs).

Table 1: Typical Decision Tree with 4 Influence Factors

Human Intervention	Available Time	Man Machine Interface	Training and Experience	Recovery Procedures	Estimated HEP Value
START	LONG	GOOD	GOOD	HELPFUL	10^{-3}, Low Value
				NOT HELPFUL	
			POOR	HELPFUL	
				NOT HELPFUL	
		POOR	GOOD	HELPFUL	
				NOT HELPFUL	
			POOR	HELPFUL	
				NOT HELPFUL	10^{-2}, Medium Value
	SHORT	GOOD	GOOD	HELPFUL	
				NOT HELPFUL	
			POOR	HELPFUL	
				NOT HELPFUL	
		POOR	GOOD	HELPFUL	
				NOT HELPFUL	
			POOR	HELPFUL	
				NOT HELPFUL	1.00 , High Value

2.2. The DT of HORAAM

The IFs of HORAAM were selected by the developers after crisis exercises. Thereafter they conducted interviews of several crisis experts. These interviews were used, on one hand to validate the pre-selected IFs and to rank them in function of their decreasing influence (cf. 2.2.1), and on the other hand to quantify the HORAAM DT (cf. 2.2.2).

In order to elaborate this model, data were collected from different crisis centers (IRSN, headquarters of EDF, plants). Different series of reactors and different scenarios were observed too.

2.2.1 The influence factors of HORAAM

From the observation of crisis exercises, developers identified several influence factors which particularly affect human and organizational reliability in a situation of core meltdown. Finally, the DT of HORAAM is constituted of the following seven IFs, each of them having 2 or 3 modalities. They are ranked in descending order of influence in table 2.

Table 2: The 7 IFs of HORAAM

	Influence factors	Description
1	**Time for decision**	The time necessary to obtain, check and process information and make a decision about the required action. This influence factor has three modalities “short” “medium” or “long”.
2	**Information and measurement means**	This IF refers to the quality, reliability and efficiency of all measurements and information available in the control room and means of transmitting them to crisis teams. This influence factor has two modalities “satisfactory” or “unsatisfactory”.
3	**Decision difficulty**	This IF refers to the difficulty in taking the right decision. This influence factor has three modalities “easy” “medium” or “difficult”.
4	**Difficulty for the operator**	The difficulty of the action (quality of the procedures, experience and knowledge in the control room or in the plant) is evaluated independently of work conditions. This influence factor has two modalities “easy” or “difficult”.
5	**Difficulty induced by environmental conditions**	This IF takes into account the on-site conditions in which the actions decided upon, have to be performed (radioactivity, temperature, smoke, gas, exiguity...). This IF has two modalities “normal” or “difficult”.
6	**Scenario difficulty**	This IF refers to the difficulty of the global context of the current accident scenario in which a decision must be made. This influence factor has two modalities “easy” or “difficult”.
7	**Degree of involvement of the crisis organization**	Local crisis organization on the plant site or the whole national crisis organization. This influence factor has three modalities “not involved”, “local crisis team involved” or “local and national crisis teams involved”.

2.2.2 Quantification of the DT

For the quantification of the DT of HORAAM, developers turned to expert judgement through interviews of the crisis experts. Even if each IF has only two or three modalities, the DT of HORAAM has about one hundred branches. This is obviously a too large number to obtain a statistical result for each branch. Another classical technique of quantification would be asking to the crisis experts to give a mark to the influence of the seven IFs and then converting these marks into probabilities but this way of doing is not correct because of dependencies between IFs.

Therefore, developers turned to an alternative method where IFs were considered in triplets or doublets. Several triplets which were identically identified by most of the different experts were used as anchor values of the DT. So, the triplets that were identified to lead undoubtedly to the success of actions were associated to a failure probability of 10^{-4} (the lower probability of the DT), those which were identified to lead undoubtedly to the failure of actions were associated to a failure probability of 1. Between these branches a non-quantified area of the DT remained. In order to quantify the remaining branches, the developers used favorable and unfavorable doublets (with a sufficient agreement between the experts), associated with the marks given by the experts.

3. QUICK OVERVIEW OF THE FUKUSHIMA-DAIICHI NUCLEAR ACCIDENT

The Tohoku district-off the Pacific Ocean earthquake occurred at 14:46 on March 11, 2011. The three units of the Fukushima-Daiichi nuclear plant which were operating were automatically shut down. Due to the earthquake, the external power supplies failed but emergency diesel generators started to carry on the cores cooling. However, one hour later, a tsunami flooded the site and degraded most of the diesel generators, most of the switchboards and most of the batteries. On unit 3 only, batteries remained available. In the main control room of unit 1 and unit 2, light, reactor parameter measurements and active cooling systems were lost.

On unit 1 a semi-passive system did not operate for complex reasons linked to the closing of some valves. The reactor was no longer cooled and the core began to melt down about two hours after the tsunami. Water injection in the vessel began only at 6:00 on March 12 through fire-trucks, probably too late to prevent vessel failure.

On unit 2, just before the loss of all AC/DC power source, the shift team manually started a steam-driven cooling system (Reactor Core Isolation Cooling: RCIC) that operated for around 70 hours without any other operation of the operators (except for the shifting of water sources from the condenser to the torus). Due to the failure of electrical supplies and the loss of all measurements on the reactor, the operators were unable to check the status of the RCIC (flow rate) for hours. RCIC failed on the 14th of March and water injection were resumed (through fire-trucks) only after more than 7 hours. No water injection for more than 7 hours resulted in a core melting (of which the extent is still difficult to precise).

For unit 3, the situation was slightly different because batteries remained available. However the safety systems RCIC and HPCI finally failed on the 13th of March. Delays in opening the safety valves in order to decrease the vessel pressure to be able to inject water through fire-trucks caused a core melting. As for unit 2, it is still difficult to evaluate its extent.

From the early moment of the tsunami arrival, working conditions of the operators were very degraded on the site. These elements are analyzed in chapter n°4 thereafter.

4. EXPERIENCE FEEDBACK FROM FUKUSHIMA

The first step of the study carried out by IRSN consisted in determining the scope of the analysis. It was decided to concentrate on the first few days that followed the tsunami. Although differences in design exist, it was admitted that the ultimate actions consisting in water injection and depressurization could be compared in the case of a similar accident in a PWR. Just below are presented the context factors that had a large impact on the implementation of actions at Fukushima. In chapter n°5 "Evaluation of HORAAM" these context factors will be confronted to the IFs of HORAAM.

This study, performed in 2012, was based on public information on the Fukushima accident available at this time (mainly reference [1]) and IRSN understanding. Some misunderstandings are obviously possible.

4.1. Unavailability of the Safety Parameter Display System (SPDS)

The Fukushima nuclear power station was equipped with the Safety Parameter Display System (SPDS) for collecting the main data from the different units, as the state of the valves and the pumps, the thermohydraulic parameters… Usually SPDS is available in the main control room, but also in the local crisis center and at the headquarters of TEPCO. Thereby, all actors involved in the crisis share actual data to assess the situation.

But, after the tsunami, because of the total loss of electrical power, SPDS was unavailable. Information from the main control room was delivered to the other actors of the crisis by phone. Information sharing was slow and some pieces of information were lost.

For example, the Local Crisis Team (LCT) was informed late about the manual stop of the HPCI of unit 3. Moreover operators could not open a relief valve to decrease the pressure in order to start low pressure injection and, as a result, the core melted few hours later. Had the LCT been aware of the situation, they might have taken actions to avoid the core melting.

4.2. Communication between the main control room and the field operators

Ordinarily, the crew in the main control room communicates with the field operators by mobile phones. But at Fukushima, the mobile phones were unavailable which had the effect of slowing down the safety actions implementation. To get information, the crew always had to wait for the operators return from the field. Moreover, facing unexpected situations, field operators always had to come back to the main control room to receive instruction from the crew. The complex actions could take hours, as for the first venting of the containment of the unit 1 (four hours were needed).

4.3. No data from sensors – erroneous data

Rapidly after the tsunami, on units 1 and 2, batteries were lost and no data about the reactors status were available. This has affected the operation of both reactors and operators spent a lot of energy trying to retrieve data. But these obvious consequences were not the only ones. The main consequence was that, ignoring the real status of each reactor, the crisis organization had difficulties to prioritize actions.

4.4. Darkness in MCR and outside

Because of the station blackout part of the work was performed in complete darkness either in the MCR or outside the MCR. Operators used flashlights or even their mobile phones. It made it difficult sometimes to locate a valve or to find a way through passageways or rooms in some areas of the plant.

4.5. High dose rates

Dose rates grew up over time. It is the first cause of failure for human actions. Operators had to use full-face masks and charcoal filters and to wear level B or C clothes or coveralls even inside the building of the units 1 and 2, which slowed down all the operations.
Moreover, in order to implement actions outside the MCR, teams were sent in turns to the work site. Despite this, several actions couldn’t be implemented due to the high level of radiation.
It has to be noticed too that the fire trucks drivers from NANMEI Company stopped working claiming their right of withdrawal: dose rates were beyond the scope of their contract.

4.6. Seismic aftershocks

During the few days that followed the tsunami, seismic aftershocks were numerous. They contributed to slow down the implementation of actions outside the MCR. On the way to their work, they could stop field operators who had to turn back to the Seismic Isolation Building.
Site Superintendent Yoshida knew that the seismic aftershocks endangered the field operators’ life and it was a reason for him to limit actions outside the MCR.

4.7. Flooding and debris

Following the tsunami, buildings were flooded. Many components were unavailable and in addition, due to the remaining level of water, local actions were impossible in several rooms. Even the checking of the RCIC operation on unit 2 was not possible because the level of water was higher than the boots of the field operator who was sent there. When they opened the door, water gushed out of the room and they could not go in.

Another consequence of the tsunami was large areas of the site littered with debris. It took five hours to drive to unit 1 a fire truck which was parked close to unit 5. Debris were removed by hand.

4.8. Hydrogen explosions

Hydrogen explosions occurred three times (on units 1, 2 and 4). The first one occurred on unit 1 on the 12th of March (the day following the tsunami): five workers were injured in the explosion. Each time the explosion strongly disturbed the actions outside the MCR. Some workers rescued the injured people from the site and the others were evacuated to the Seismic Isolation Building. Investigations were carried out and any recovery work could not start again before the area was deemed safe. On reactor 3, water injection was indeed interrupted for almost six hours after the hydrogen explosion. Moreover hydrogen explosions have disrupted the work in progress.

5. EVALUATION OF HORAAM

Influence factors are ranked in the decision tree by decreasing order of importance. The first step of the study was the assessment of the IFs: the choice and the ranking. The confrontation of HORAAM to experience feedback from Fukushima shows that both were good. It confirms that the first two IFs "Decision period" and "Information and measurement means" are essential. If these IFs are disabled the mission will probably fail. In the PSA meaning, the action is considered "not implemented" or "implemented too late to avoid a degradation" (the core meltdown or the failure of a component).

5.1. Validation of the first four IFS of HORAAM

The first four IFs are validated without modification:

- IF n°1 "Time for decision"

The IF "Time for decision" is the first IF in HORAAM, so this IF is considered as contributing the most to the success or the failure of a mission. Experience feedback from Fukushima confirms this importance but some considerations can be added. The time before core degradation (few hours) was short for the reactor 1 and it was not sufficient for a correct diagnosis of the reactor status, taking into account the instrumentation unavailability. For the reactor 2 and 3, the time before core degradation was longer (70 hours and 40 hours), but the time available from decision to action implementation was not sufficient. Considering the degraded situation, it took a long time to implement all the actions, even the simplest ones. A short time available in degraded situation obviously leads to failure. One lesson may be that the notion of "short time available for HRA" is longer in a degraded situation, as it was the case at Fukushima, than the one in "normal" environmental conditions (around ten hours in degraded situation compared to around one hour in "normal" environmental conditions).

- IF n°2 "Information and measurement means"

Just after the tsunami, reactor 1 and 2 have lost all Direct Current (DC) power supplies. As a result the operators were unable to monitor plant parameters including the reactor water level. One direct consequence was that they were unable to apply the EOPs because there was no procedure taking into account the events where all Alternative Current (AC) and DC power sources would be lost. Moreover, SPDS was unavailable, even for unit 3, so the crisis teams had to try to understand the situation at each unit based on information obtained by phones. Site Superintendent thought it would be impossible to take any action necessary to control the nuclear plants without the plant parameters, especially those for the reactor water level and pressure. He put a priority to restore equipment necessary to measure the main reactors parameters to the detriment of other actions.

• IF n°3 “Decision difficulty”

Considering the lack of electrical power supplies and the batteries depletion, pumps or valves had to be operated locally, directly on the component. Each of these actions endangered the health of the field operators through dose rate, seismic aftershocks and hydrogen explosions. Site Superintendent who coordinated the operations was also responsible for the radiological releases outside the plant and the protection of the health of the operators in the plant. His decision was a compromise between the plant operation and the protection of the health of the field operators.

• IF n°4 “Difficulty for operators”

The IF n°4 “Difficulty for operators” is designed to sort actions well known by operators (normal operation or well-trained operations on simulators) from actions that operators implement rarely as unusual pipes alignments.
At Fukushima, after the loss of the safety injection means (IC, RCIC, HPCI), operators had use mobile water injection means and they had to face difficulties:

- workers from NANMEI Company who were used to driving and operating the fire trucks stopped working because of dose rates ;
- TEPCO operators were not skilled to operate the fire trucks for water injection into the core of the reactors ;
- no procedures were available, especially for connecting the fire hoses of the fire engines to the fire pumps discharge ports outside the turbine building.

At Fukushima, the long duration to put into operation this alternative water injection demonstrates, if necessary, the importance of IF n°4.

5.2. Comments about IFS n°5 to n°7

Based on the analysis of the Fukushima accident, IFS n°5 to n°7 don’t appear to be inappropriate but comments are needed:

• IF n°5 “Difficulties induced by the environmental conditions”

The Fukushima accident shows (cf. 4.4 to 4.8) how bad environmental conditions can slow down the implementation of actions. Moreover, several operations were cancelled because of the high level of dose rate. The relevance of IF “Difficulties induced by the environmental conditions” is not to be questioned but on the contrary, it appears that this IF has a too low influence on the resulting probabilities. Therefore, HORAAM should be updated to reassess IF n°5.

• IF n°6 “Difficulty of the scenario”

As it was the case for IF “Difficulties induced by the environmental conditions”, the relevance of IF n°6 “Difficulty of the scenario” is not to be questioned. Surely the situation at Fukushima induced by the external hazard of an earthquake and a tsunami, the total loss of electrical power, the loss of the heat sink and the meltdown of the core of tree units is a difficult scenario. All these elements induced difficulties to implement any action. However, it appears that difficulties induced by the type of scenario are already included in the other parameters of HORAAM. The crisis experts who were interviewed for the development of HORAAM had highlighted the interest of a particular IF “to take into account multiple failures” but finally the process of quantification (based on the interviews of the same experts) attributed a low influence for this IF. So, after this study, the suppression of IF n°6 is recommended.

- IF n°7 “Degree of involvement of the crisis organization”

The IF n°7 “Degree of involvement of the crisis organization” is correlated to the attendance of crisis teams. Four hours after the occurrence of an initiating event, the French crisis organisation is supposed to be available and its influence no longer changes. In HORAAM, IF n°7 concerns only medium and long durations. The failure probability of a human action decreases slightly when the local crisis team is available and it decreases a little more when the national crisis organisation is available. Of course the experience feedback from Fukushima does not question the relevance of an IF dedicated to the crisis organization but it is important to note that the crisis organisation has to manage simultaneously many priorities when several units of a nuclear site are damaged. HORAAM should take into account this lesson. Therefore, IF n°7 “Degree of involvement of the crisis organization” would become “availability of the crisis organization for the unit management” with tree modalities “1: Only the crew is available” or “2: the local crisis team is available” or “3: the national and the local crisis team are available together”. Yet, for each action, the modality of IF n°7 would be fixed depending on the state of achievement of other actions, either on the same unit or on other disabled units. For the latter case, HORAAM could be used for site PSAs.

6. CONCLUSION

The purpose of the IRSN study was to confront HORAAM, its HRA model for level two PSAs, with the difficulties encountered at Fukushima to implement actions after the core meltdown. At Fukushima, most of the data needed to operate the units were unavailable, communication means were disabled, the system to share information between all the crisis actors was unavailable, hours after hours dose rate increased, part of the work was performed in a complete darkness, the ground was littered with debris, the basements of the buildings were flooded, often works in process were interrupted by seismic shocks, and worse, hydrogen explosions endangered the life of field operators.
With a DT HRA model, as HORAAM, the IFs assess the context of a human action in order to derive its failure probability. The choice and the ranking of the IFs are essential. The study confirmed that the first four IFs: “Decision period”, “Information and measurement means”, “Decision difficulty” and “Difficulty for operators”, were well selected. If these IFs are poorly rated, the human action will probably fail.
However, the study concluded that the last three IFs called for comments. These IFs are not indeed inappropriate but improvements need to be made. IF “Difficulty of the scenario” is relevant but it is redundant with several other IFs and it can easily be suppressed. IF “Difficulties induced by the environmental conditions” is essential. It must be kept and its influence on the quantitative results should be increased. Lastly, IF “Degree of involvement of the crisis organization” which only relies on the presence of the crisis organization should be adapted to take into account the extent of the crisis organization operationality (depending on the number of simultaneous tasks to be performed simultaneously). This evolution would also result in extending the scope of HORAAM to the assessment of several units together (site PSAs).

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