An analysis of criticality safety ”near misses”

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AN ANALYSIS OF CRITICALITY SAFETY "NEAR MISSES"

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ABSTRACT

Among the criticality safety events reported to the nuclear safety authorities, that have occurred in nuclear facilities around the world, some have been of particular concern and are usually referred to as "near misses". They can be classified in different categories: some actually came close to critical conditions, or these conditions remained remote but were narrowly avoided thanks to an emergency human intervention, others occurred in otherwise favorable situations (margins resulting from other variable parameters) but could have come close to critical conditions assuming other authorized or possible parameters. Finally, other events would have remained far from critical conditions even potentially, but are nevertheless also considered as "near misses" for other reasons, for example serious breaches of the rules, a significant impact on the activities (shutdown), etc. In addition to these different categories of consequences, "near misses" can also be classified according to the types of original deficiencies that caused them: physical phenomena that were not previously known, lack of awareness of the importance of certain safety measures and consequently of rigor in their application, lack of basic criticality safety training, differences between the conditions described in the safety documents and those actually encountered, or simply a "detail" that escaped the vigilance of the operators or safety teams.
This paper presents a "double classification" of 25 "near misses" according to both the original deficiencies and the types of consequences explained above, by briefly presenting the elements leading to these choices of categories.

KEYWORDS

Near misses, events, consequences, deficiencies

1. INTRODUCTION

Among the reported criticality safety events that have occurred in nuclear facilities around the world, some have been of particular concern and are usually referred to as "near misses". On January 11th, 1989, the French Criticality Safety Commission (CSC, a group of experts that used to support the French nuclear safety authority) classified 12 domestic events as “near misses” events and sorted them according to different types of original deficiencies (described in chapter 3.1).

An update of this analysis based on the so-called LOGIC, IRSN “Learning From Experience” (LFE) database dedicated to criticality safety events, presented in [1] and briefly in chapter 2, leads to classify 25 events as “near misses”. Those 25 events include the 12 French near misses identified in 1989. We have selected 13 other events that occurred between 1983 and 2017 in France and in the USA. We have sorted them according to the types of original deficiencies, and also according to different categories of consequences (described in chapter 3.2), corresponding to different definitions of the notion of "near misses". We describe some events as example with elements justifying these classifications. Finally, in chapter 4, the distribution of the 25 near misses according to the different types of original deficiencies, categories of consequences and levels of involvement of human and organizational factors (HOF) is analyzed.

2. LINK BETWEEN THE CRITICALITY SAFETY ANALYSIS GUIDE AND THE LOGIC EVENT DATABASE

As explained with more detail in [1], the IRSN has published a criticality safety analysis guide describing the methodology to follow to perform a criticality safety analysis or assessment. The guide presents the French criticality safety regulations and contains several diagrams, each diagram presenting questions related to a given category of questions. These categories are control modes (mass of fissile material, geometry, moderation, concentration, homogeneous or heterogeneous poisoning) and reference fissile media used to ensure subcriticality in non reactor facilities, equivalent notions for reactor loading and unloading operations (the aforementioned control means except mass and concentration, and also fissile media), neutronic interactions or reflections, and criticality accident categories (detection, protection or means to stop an accident).

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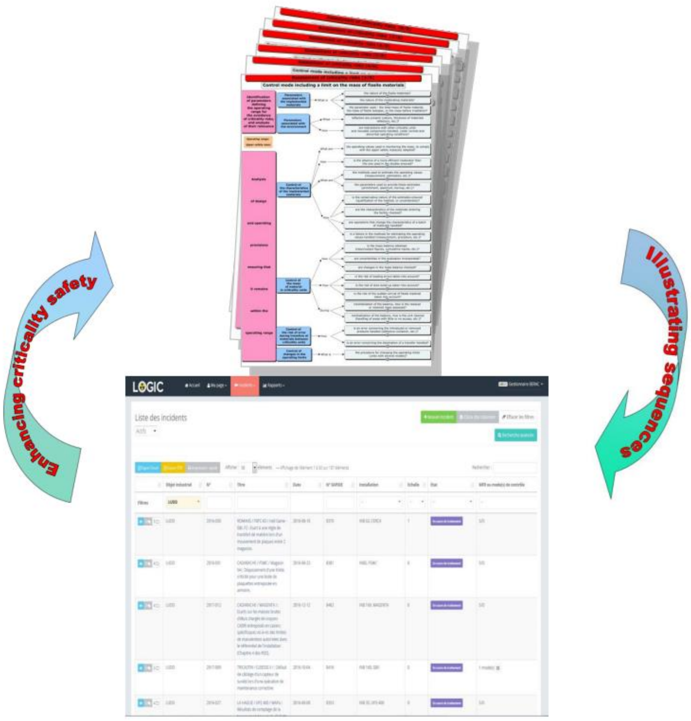

Figure 1. Link between LOGIC database and the IRSN criticality safety guide

Besides, the LOGIC event database is continuously updated with the declared criticality events from licensees and their analysis by IRSN. In particular, each criticality event is classified according to one or more types of failures involved, that can be chosen in LOGIC and are linked to the issues described in the aformentioned diagrams of the IRSN criticality safety analysis guide. The analysis of criticality events has allowed to identify failures that had no corresponding issues in the diagrams of the preceeding version of the IRSN guide (in 2010) and to complete these ones in the latest version of the guide (in 2022), thus participating in enhancing nuclear criticality safety, as shown in Figure 1 above.

The main objective of events analysis is to identify failures, encourage preventive and corrective actions to avoid the recurrence of these failures, in all the facilities that could experience the same failures.

3. CLASSIFICATION OF NEAR MISSES

3.1. Original deficiency

To classify the 12 "near misses" identified in 1989 (see chapter 1), the CSC sorted them according to 5 types of original deficiencies:

- A. a "detail that was missed" (3 events);
- B. lack of knowledge or underestimation of a physicochemical phenomenon (2 events);
- C. inadequacy between safety report and reality (2 events);
- D. lack of basic criticality training (2 events);
- E. lack of knowledge or forgetting of the purpose of safety measures (3 events).

These types of original deficiencies should not be confused with the scenarios chosen in LOGIC to characterize the events (see chapter 2). For example, the uncontrolled accumulation of fissile material is a scenario that can be caused by different original deficiencies such as the lack of knowledge of the physical phenomenon of accumulation (type B) or the loss of the accumulation periodic monitoring purpose (type E). The scenarios are much more numerous than the types of original deficiencies.

In addition to extending this classification to 13 other near misses, IRSN made further investigations into the 12 near misses considered by the CSC and conducted its own analysis of the original types of deficiencies. Discussions were held between IRSN and the former CSC Chair. The near misses described below are examples for each type of original deficiency.

Example #1. In France, in the 70s, some acid uranyl nitrate solution was unintentionally transferred to an already full annular tank, whose central part was filled with paraffin and coated with cadmium foil (neutron poison). The acid solution overflowed and attacked a small part of the cadmium which was sticking out of the paraffin protecting it. This caused a heating that melted the paraffin, freeing a larger surface of cadmium, whose attack by the acid caused an increasingly important heating and a release of gas. This gas transformed the paraffin into foam and ejected it from the tank, so that it inhibited the flood detector at the bottom of the glove box. The fissile solution filled the volume originally occupied by the paraffin in the tank (see Figure 2), whose geometry was unsafe. This was a **type A original deficiency**, due to several missed details: cadmium sticking slightly out of the paraffin, a faulty warning light that did not signal the unintended transfer control, an overflow orifice to an adjacent empty annular tank that became clogged with machining chips floating on the solution surface (chips that had been present since the ring tank was fabricated and were not detected) and a vent that was too vertical and led to solution overflowing toward the center of the tank (not outside).

Example #2. In France, in the 70s, an abnormal high mass of plutonium had been accumulated slowly in a dissolver for natural uranium - graphite - gas reactor assemblies, by being adsorbed on precipitates of zirconium phosphates (a fission product). These precipitates were generated by the presence of residues of tributyl phosphate or its decomposition products in the acid and water used in the dissolver, because it was recycled water and acid. This was the result of physico-chemical phenomena unknown at the time, and thus a **type B original deficiency.** After the event, the identification of these phenomena required a lot of time, studies and tests and led to put in place means to:

- recover the precipitates (first basic rinses to "break" them, then boiling acid rinses, which required circulating these acids to the ancillary equipment without heating systems...);
- continue to use the large stock of recycled acid, but after forced precipitation with zirconium and filtration to limit the formation of plutonium-adsorbing precipitates;
- use a new dissolver equipped with a neutron counter to monitor the formation of precipitates, see Figure 3.

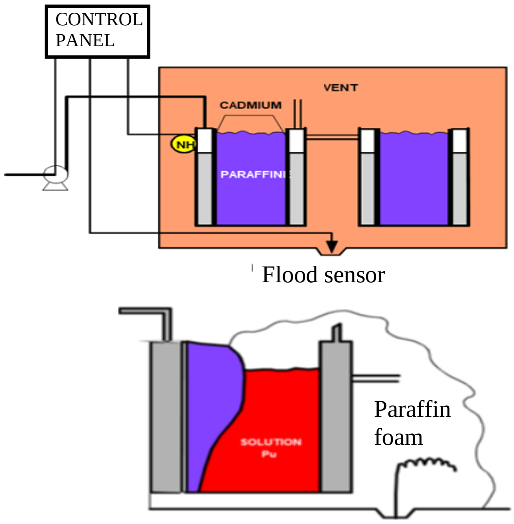

Figure 2. Type A, France, 70s

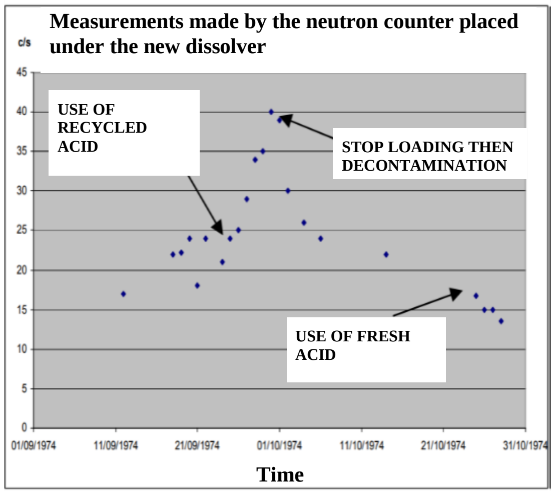

Figure 3. Type B, France, 70s

Example #3. At BWXT (USA) in 2007 [2], a vacuum cleaner, containing Raschig rings and filled with a uranium solution, was packed in two bags and transferred by two workers to a radiological control area. Because of the physical effort required to climb an access ramp, one of the workers let the handling support fall, and the vacuum cleaner was also poorly attached to this support. The vacuum canister and the inner bag were punctured on impact. The uranium solution leaked into the outer bag in an unsafe geometry and was separated from the Raschig rings, which partly came out of the vacuum canister, but remained in the inner bag (see Figure 4 below). It was **a type C original deficiency,** because the handling conditions were not analyzed in the safety report and were not known by the criticality safety specialists, who indicated that this knowledge would have led them to recommend more restrictive limits on the contents authorized for transfer.

Figure 4. Type C, BWXT, 2007

Figure 5. Type D, LANL, 2011

Example #4. At Los Alamos (USA) in 2011 [3], an event occurred in a context where criticality safety teams had tensions with their management leading to shortcomings in oversight and operational guidance. This event caused an "exodus" of criticality safety engineers, the shutdown of several facilities for several years and difficulties in reconstituting safety teams. A worker gathered plutonium metal objects normally handled at workstations separated by minimal distances, in order to take photographs (see Figure 5) and without being aware of the criticality risk. In addition, a supervisor, noting this failure to respect the minimum distance requirement, made a second error by asking the worker to separate the parts immediately, instead of taking the usual precautions after the detection of such an anomaly, i.e., evacuating the personnel and defining safe intervention conditions to return to a normal situation. **The original deficiency was thus of type D** (lack of criticality safety training).

Example #5. At the time of this event, that occurred at the Dampierre PWR reactor in France in 2001 [4], there was a lack of communication between the teams in the reactor building (BR) and the fuel building

(BK), and the fuel assemblies were loaded into the core sequentially without checking their individual references in the BR (an organization that was subsequently improved). Following a change of roles of several workers in the BK team, a fuel assembly was left in the BK pool, although the sheet indicating its transfer to the BR had already been filled in beforehand to save time. The omission of this assembly led to a shift in the position of 113 consecutive assemblies in the core (see Figure 6). The error was detected in the BR by noting the association of an assembly with an neutron absorbing rod of the wrong type. This detection was delayed because some of the required controls have been skipped (matching of absorbing rods and assemblies rarely checked in the BR, no search for the cause of the missing signature on the transfer sheet during the review of the sheets in the BK). **The original deficiency was thus of type E** (forgetting the purpose of safety measures).

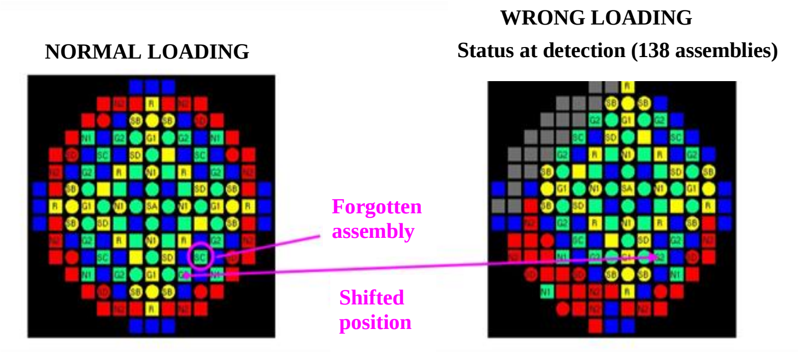

Figure 6. Type E, Dampierre, 2001

Example #6. This event occurred at Wilmington, USA, in 1991 [5]. Buffer tanks V290 and V291, of safe geometry, were used to control samples of the aqueous phase from an extraction column. These samples were then sent to a large tank V103 of unsafe geometry where they transited before being accumulated in a second tank V104 (identical to V103). In this second tank, samples were centrifuged and precipitated (see Figure 7). The failure of the LCV valve, controlling the level of the interface between the solvent and the aqueous phase in the extraction column, led the staff to force the valve open, rendering the extraction ineffective. Anxious to maintain production (in a general context of industrial pressure), the staff did not immediately cut off the solvent supply, which led to the rapid filling of the buffer tanks V290 and V291 with solutions with abnormally high uranium concentrations. Many samples were either sent directly to tanks V103 and V104 without being controlled (in order to empty the buffer tanks), or were controlled, but their uranium concentrations were largely underestimated, probably because these concentrations were well beyond the validity range of the sample analysis system. Later studies showed that some samples had reached 12000 ppm of uranium, whereas the authorized limit for sending them to tanks V103 and V104 was 150 ppm. Finally, 150 kg of uranium were accumulated in tank V104, normally limited to 35 kg of uranium. After discussions with the NRC (Nuclear Regulatory Commission), the plant manager belatedly became aware of the seriousness of this event. The bubbling system of the V104 tank was used continuously to prevent settling that could lead to the gathering of a critical uranium mass. The failure of the bubbler system was feared because of its unusually high loading, so gathering of neutron poisons was made to stop a criticality accident if it occurred. After the event, a NRC investigation of the history of the plant revealed that, to facilitate production, several redundant controls had been progressively eliminated or bypassed ("compromises" had been accepted by the safety engineers), so that bubbling in V104 remained the only reliable safety measure, provided it was not used in an extreme manner as in the event. **The original deficiency was thus of type E.**

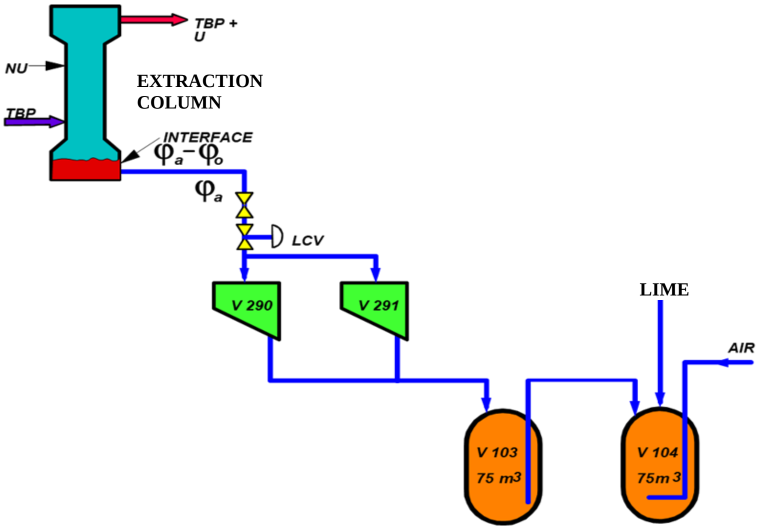

Figure 7. Type E, Wilmington, 1991

3.2. Consequences

The most traditional definition of a "near miss" is an event whose consequences were close to, but did not reach, accidental conditions. After examining the reasons for the classification as "near misses" of the 12 criticality events considered by the CSC in 1989 and of other events considered as such in France and in the world, it appeared that the notion of "near miss" includes events with different levels of real or potential consequences. The following categories of consequences have then been identified by IRSN:

- 1. real approach to critical conditions;
- 2. approach to critical conditions prevented by a human emergency action;
- 3. potential approach to critical conditions in other authorized conditions;
- 4. critical conditions remained away, even potentially, but event considered as a "near miss" for other reasons (important impact on the activity such as important industrial modifications or prolonged or even definitive shutdown, very worrying breach of operating rules, etc.).

The example #2 (slow accumulation of plutonium in a dissolver, see chapter 3.1) was a near miss with **type 1 consequences**. The precipitates initially resisted the acid rinses at the end of the dissolution campaigns, which led to an accumulation of 3.5 kg of plutonium, to be compared with the minimum critical mass of 775 g for PuO_2F_2 with 13 % plutonium 240, moderated and reflected by water. It was considered that the critical conditions were close.

The examples #5 and #6 (see chapter 3.1) were near misses with **type 3 consequences**, as shown by the conclusions of their subsequent analysis :

- for the example #5 (shift of assemblies in a PWR core at Dampierre), studies showed significant safety margins in the conditions of the event (boron content in the water of 2350 ppm and burnup of the assemblies), but the critical conditions could have been reached if 121 assemblies (instead of 113) had been shifted and with more unfavorable, but authorized, conditions (boron content of 2000 ppm, lower burnup);
- for the example #6 (uranium sent into a tank of unsafe geometry at Wilmington), studies were based on data that could not be controlled and limited in practice during operation, namely feedback on the relative amounts of various types of material mixed in tank V104 and experimental data on their different settling rates. These studies showed that, if the bubbling system had failed, a criticality accident would have been unlikely with the 150 kg of uranium actually accumulated in the V104 tank during the event, but the accident would have happened

if the process had not been interrupted and had led to the accumulation of the 275 kg of uranium present in the batch being treated.

The example #1 (degradation of cadmium and paraffin in an annular tank, see chapter 3.1) was also a near miss with **type 3 consequences**. Subcriticality was maintained thanks to the concentration of uranium limited to 10 g/L, but a criticality accident could have occurred with the maximum authorized concentration of 50 g/L, even taking into account the poison-absorbing effect of dissolved cadmium.

Types 2 and 4 consequences are illustrated by two new examples described below.

<u>Example #7</u>. From a chemical reaction involving mixed powders of UF_4 and calcium ($UF_4 + 2\ Ca \rightarrow U + 2\ CaF_2$), calciothermy leads to a metallic uranium cake superimposed on a slag of fluorite CaF_2. An event at Y12 NSC (USA) in 2017 [6] concerned equipment used to crush and sift slag after removal of uranium. After the event, in situ measurements revealed 4.14 kg of uranium 235 (about 5 times the minimum critical mass with moderation and reflection by water), in retention in an unsafe geometry (box receiving uncrushed slag fragments, chute and sieve-like sand separator, see Figure 8). The earlier event was a water leak that nearly led to water entering the chute and creating critical conditions, but a worker cut off the water supply just in time (water was only mixed with a thin layer of sand), so this was **type 2 consequences**. Retention was due to slag fragments that had overflowed from the receiver box and entered the chute. This was caused by the absence of periodic emptying of the box, foreseen in the design, but finally abandoned, since the quantity of fragments was negligible when the calciothermal process was functioning correctly. But its quality had progressively deteriorated, resulting in an imperfect separation between uranium and fluorite, making it more difficult to crush slag and leading to more fragments with more uranium. Periodic emptying of the receiver box became necessary.

<u>Example #8</u>. In France in the 70s, sheared pieces of fuel assemblies were poured and dissolved in a tube without the basket normally inserted in it (see Figure 9), which led to an increase in reactivity because the pieces of assemblies were distributed in a larger section than the basket considered in the criticality studies. This basket had remained hooked to the handling clamp. The mechanical cause was that the basket release signal was generated not from the actual state of the clamp, but from an air pressure feeding the pneumatic control of an air jack. This pressure was sufficient to activate this signal, but insufficient to release the basket, because of a sealing defect (worn spherical valve). The release of the shear cutting the assemblies required the closing of the tube caps, which was done by jacks. The use of these jacks was a development implemented without informing the safety engineers who, in the initial design, had planned for the caps to be placed using the same unique clamp that was also used to handle the baskets. This initial design would have made the event impossible, since the caps could only have been closed if the clamp was free and the baskets already in place in the tubes.

This example #8 was a near miss with **type 4 consequences**, because dissolver had remained unavailable for two months, and the improvement of the clamp system had required four years of study and testing (it consisted of installing microvalves and flow indicating the actual state of the cylinder operating the clamp and thus its open or closed state). Nevertheless, critical conditions could not be reached, even potentially. Indeed, criticality studies carried out after the event showed significant margins with respect to the critical conditions, considering the burn-up of the assemblies after irradiation, the real kinetics of the dissolution (faster than that assumed in the studies), the real enrichment of the uranium at the time of the event, and even potentially the maximum authorized uranium enrichment.


Sand separator (left) and slag chute with can (right)

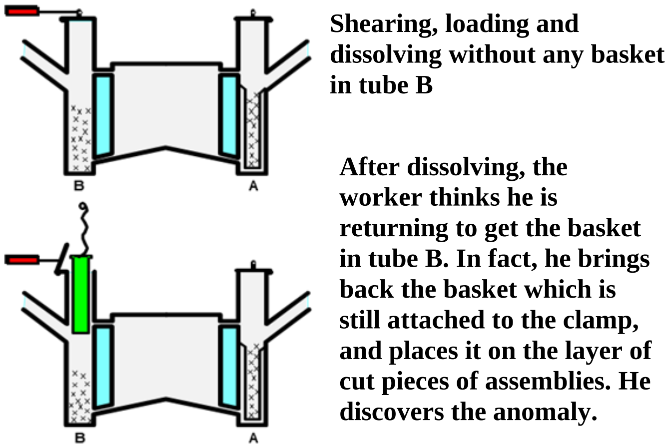

Figure 8. Type 2, Y12 NSC, 2017

Figure 9. Type 4, France, 70s

4. RESULTS OF THE ANALYSIS

The distributions of the 25 near misses considered (see chapter 1), according to original deficiency types A to E and consequence levels 1 to 4 are presented on Figure 10. Also, the Table 1 shows a "double classification", with the types of original deficiencies in rows, the types of consequences in columns and the numbers of events in each cell, corresponding to an association between given types of original deficiencies and consequences.

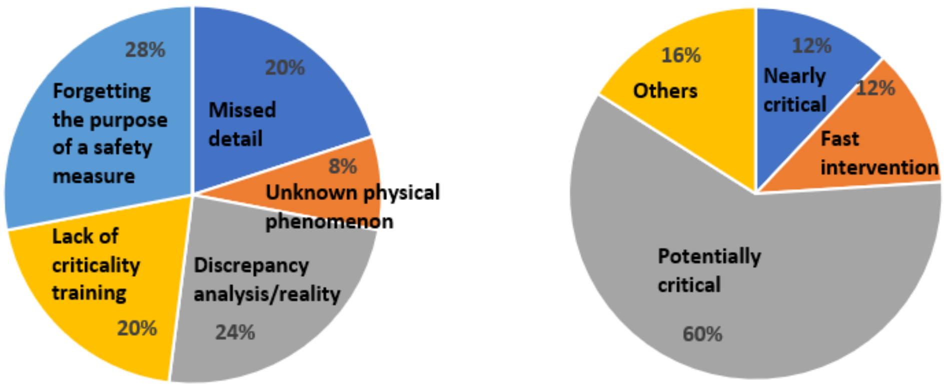

Figure 10. Distributions of the near misses according to original deficiency types (left) and consequence levels (right)

Table I. Distributions of the near misses according both to original deficiency types (rows) and consequence levels (columns)

Consequences / **Original deficiencies**	Type 1 : Nearly critical	Type 2 : Critical conditions avoided by a fast intervention	Type 3 : Potentially critical in other authorized situations	Type 4 : Others (*)	**TOTAL**
Type A : A detail that was missed	1		3	1	5 (20 %)
Type B : Unknown or underestimated physical phenomenon	1			1	2 (8 %)
Type C : Discrepancy between analysis and reality			5	1	6 (24 %)
Type D : Lack of criticality training		2	3		5 (20 %)
Type E : Forgetting the purpose (or lack of knowledge) of a safety measure	1	1	4	1	7 (28 %)
TOTAL	3 (12 %)	3 (12 %)	15 (60 %)	4 (16 %)	25

(*) critical conditions remained away, even potentially, but events considered as near misses for other reasons (long term or even definitive shutdown, very worrying breach of operating rules, etc.).

Type 3 consequences (potential criticality in other situations) gather most of the near misses. We also see that near misses are almost uniformly distributed among original deficiency types, except for the lack of knowledge of a physical phenomenon, that is less frequent if we consider all the 25 near misses up to 2017. This was not the case with the 12 events considered by the CSC in 1989 (their numbers for the different original deficiency types are presented at the beginning of chapter 3.1). Of course, considering a more or less stable set of processes in nuclear facilities, physical phenomena that were initially unknown will be more and more known and controlled. But we are currently in a period of renewal of nuclear facilities, with may be the implementation of new types of reactors and new processes (fabrication and recycling of new types of fuel assemblies), and we could again be confronted with underestimated or unknown phenomena. Human and organizational factors (HOF) are little involved in this type of deficiency, so the only remedies are the completeness and validation of prior theoretical studies and the implementation of robust engineering designs and monitoring systems.

Concerning HOF, in a first approach, they are obviously :

- little involved in type B original deficiencies (lack of knowledge of a physical phenomenon);
- highly involved in type D or E original deficiencies (lack of criticality training or forgetting the purpose of safety measures), which are linked to organizational failures, concerning either the operation or the origins of the design; this last point is illustrated by the example #8 (loading of a dissolver without basket, see chapter 3.2), as the use of jacks to close the dissolver plugs may have not been discussed with safety engineers who had initially planned to use the clamp;
- partially involved in type A deficiencies ("detail that was missed"), some being errors that could have been detected earlier by better monitoring of interventions, and in type C deficiencies (discrepancy between analysis and reality), with a lack of information from staff to safety engineers;
- involved favorably in near misses with type 2 consequences, as the reaching of critical conditions was avoided thanks to a fast human intervention (see example #7 in chapter 3.2, a water leak near a cavity containing retention, and the water supply was cut off just in time).

The distribution of the 25 near misses according to HOF is presented in Figure 11.

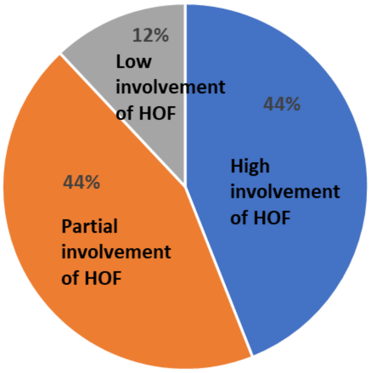

Figure 11. Distribution of the near misses according to the level of involvment of HOF

5. CONCLUSIONS

Events that occurred over a period of about 50 years, caused by different types of original deficiencies, are considered as near misses for different reasons (types of consequences, which fortunately were only potential consequences for the most part, but some events led to actually approaching the critical conditions). These near misses are of particular interest among the set of events whose feedback is used to define preventive actions aiming at avoiding the future occurrence of similar failures. As for other risks, HOF are an important component of criticality safety. But even in the case of the lack of knowledge of physical phenomena, with little involvement of HOF, the associated near misses (mostly the oldest) underline the need for vigilance in theoretical studies, in the design of new types of reactors and processes for the fabrication and treatment of new types of fuel assemblies, and more generally in all criticality risk prevention measures.

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