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Criticality Accidents Occurred in Research Reactor Facilities in France

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ABSTRACT

So far, in France, no criticality accident has occurred in a process facility. However, 3 accidents happened in research facilities. The first one, notably mentioned in [1] and thoroughly described in [2], occurred in the ALIZE critical assembly, a water reflected and moderated UO₂ assembly, at the CEA site in Saclay in March 1960. A similar event occurred in October 1968 at the same site, in the ISIS experimental pool - reactor [3]. The ISIS reactor was designed to conduct tests related to new reactor configurations of the OSIRIS core, as well as fuel and irradiation experiments. The third one occurred in 1971.

This paper presents and compares these 3 accidents, which had little or no consequences for operators and the environment, to prevent them from being forgotten due to their age, the lack of associated documents and generational replacement.

Key Words: Criticality, accidents, reactor, research

1 INTRODUCTION

Unlike French processing facilities (no criticality accidents to date), three criticality accidents have occurred in French research reactors in the 60s-70s: the ALIZE assembly (notably mentioned in [1]), the ISIS reactor at Saclay and a third research reactor on another site. This paper reminds them to share the lessons learned and to prevent them from being forgotten due to their age, the lack of associated documents and generational replacement. At last, their common features are discussed.

2 ALIZE - MARCH 15, 1960

2.1 Description of the critical assembly

The ALIZE reactor had been operated by CEA in Saclay since 1959. This critical assembly was a water reflected and moderated UO_2 system, enriched to 1.5% in ^{235}U . The 2.2 tons of UO_2 were immersed in a 2 meter diameter aluminum cylindrical tank. The assembly was composed of 5,257 aluminum clad sintered UO_2 rods arranged in a 73×73 units array with a 11.1 mm square pitch. Each rod had a diameter of 6.395 mm and a height of 1,080 mm. It also contained six cadmium plates, ensuring both safety and control, gathered two by two and inserted in the place of six groups of 12 fuel rods. The critical approach parameter was the water height in the tank. The reactor was installed in a 9 m deep pit, which was closed by two concrete slab doors at ground level during reactor operation, ensuring biological shielding. Figure 1 illustrates the core layout.

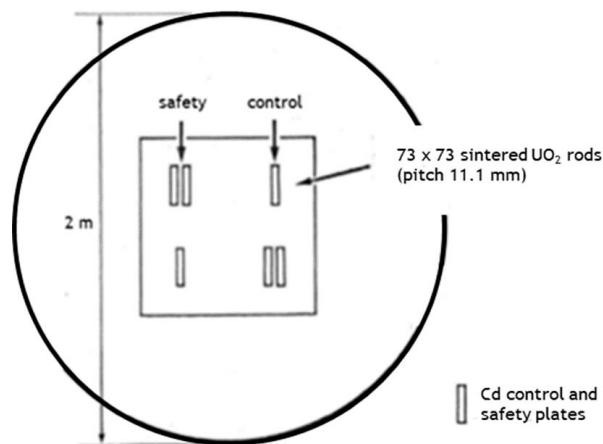


Figure 1. Horizontal sectional view of the ALIZE reactor [2]

During normal operation, ALIZE could be automatically shut down either by a safety plates drop, or by fast water dump of the tank. Those automatic scrams were triggered on thresholds on power or neutronic period based on ionization fission chambers signals.

The water filling of the critical assembly tank was only permitted if at least two groups of two cadmium plates had been withdrawn, ensuring sufficient anti reactivity in case of an emergency shutdown.

2.2 Presentation of the accident

The accident took place during an irradiation experiment of a manganese device on a long stable period to measure the radial buckling. Same experiments had been previously performed with the assembly, so the operators knew the critical water height and the expected water height for irradiation. To reach the objectives of the experiment, a reactivity excess of 50 pcm (7.7 cents) had to be produced and the shutdown was foreseen at 10 watts power. This accident has been documented in [2].

On March 15, 1960, only one operator was operating the reactor. Before starting the water filling, the safety plate #1 was removed but, for some unknown reason, the safety plate #4 was not completely removed. However, the operator started to fill the tank. At a water height of 806.5 mm, the operator noted that the counting rates was abnormally low compared to previous experiments. He then realized that a safety plate was still in the core and decided to raise safety plate #4 to mid-core position. The neutron counting rates became higher than before but still lower than expected, which should have warned him. However, he continued to fill the tank. At a water height of 845.3 mm, based on measured counting rates, he determined from extrapolation the critical water height at 902.5 mm. This value was totally inconsistent with the well-known critical water height of 846.9 mm. Despite this difference, the operator continued water filling.

At a water height of 885.1 mm, the cadmium plates automatically dropped to shut down the reactor. Following this shutdown, the operator forgot to change the sensitivity of measurement devices, which stayed on the lower sensitivity. This omission explains why the operator did not notice the slow divergence of the reactor. The operator removed safety plate #1 and raised safety plate #4 to mid-core position. He then resumed water filling. When the water height reached 906 mm, the neutronic chains detected divergence. The operator thought of an instrument error and set it to zero. This action cancelled the safety scram by fast water dump by the neutronic period threshold. He then removed completely safety plate #4.

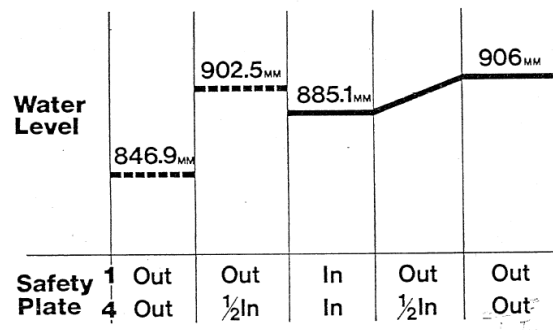


Figure 2. Evolution of water level during the experiment [2]

Although the reactor was supercritical, the safety plates failed to scram, probably because the triggering threshold had been passed too rapidly. The operator, finally looking to the reactor status, shut down the reactor manually by dropping the cadmium plates. He then started the water dump of the tank. 20 minutes after the dump, the group leader decided to fill the tank to a water height of 650 mm to avoid a heat of the fuel.

2.3 Analysis

Characteristics of the excursion were later evaluated as follows:

- excess reactivity of 950 pcm,
- initial slope of 32 pcm/s,
- total fissions equal to $3.3 \pm 0.3 \times 10^{18}$,
- temperatures in UO₂ rods likely lower than 550 °C,
- duration of the supercritical state approximately equal to 80 s.

In 1960 document, it is explained that ²³⁸U Doppler effect probably help to slow down the power pulse (Doppler coefficient estimated at -3.5 pcm/°C ± 50 %). Nevertheless, this analysis should be reviewed because it neglected boiling and radiolysis phenomena.

The core was undamaged, no cladding rupture occurred, and no contamination was measured. The estimated number of fissions was based on the activity measurement of ^{140}Ba from a spent pellet. The estimated radiation dose received by the operator was about 20 to 30 mSv.

This accident is mainly due to several human errors:

- careless manipulations of the safety plates: the historic documents do not allow to understand why plate #4 is in mid-position,
- lack of critical judgment regarding the large discrepancies of water heights and counting rates,
- failures on the use of measurement devices,
- bad selection of the power measuring chains sensibility (too low sensibility),
- allowing an operator to conduct the experiments alone - in addition, the experiment took place during lunchtime and some people were absent.

This accident resulted from numerous failures, mainly human and organizational, and some measures intended to limit the potential consequences were not functional.

3 ISIS - OCTOBER 14, 1968

3.1 Description of the critical assembly

The 700 kW ISIS reactor was a water pool neutron mock-up of the OSIRIS reactor, to which ISIS was connected through a channel, so that irradiated devices could easily be transferred between the two cores. ISIS was operated by the CEA in Saclay, from 1966 to 2019. The ISIS reactor was dedicated to neutronic measurements, notably documented in [3]. Tests of new core configurations, fuel elements or irradiation experiments were carried out by measuring the effects on reactivity, neutron flux or gamma heating. The reactor was also used for training purposes. At the time of the accident, the critical assembly was U-Al plates, with Al cladding and highly enriched uranium.

3.2 Presentation of the accident

On October 14, 1968, a neutron spectra measurements campaign had been conducted in the ISIS facility for several days. The experimental set-up included a device with a neutron counter, positioned under a thick boron container at the center of the core, located at position 25 ($X=5$, $Y=20$) of the rack (see Figure 3 below). The change of the neutron counter required completely removing the experimental setup, that is to say removing the thick boron container which is a highly efficient neutron absorber. The unloading operation had previously been carried out several times and was safely designed if the control rods #1 and #4 (in positions 14 and 36) were in low position. The control rods were composed of uranium in the low part and cobalt (Co) at the top. In low position, the uranium part was under the core and the cobalt part was at the core level.

The removal of the experimental device was carried out manually by an operator from the bridge over the core. It was during this operation that the criticality accident occurred.

After having supposedly inserted the control rods #1 and #4, an operator located in the control room gave the order to unload the experimental device to another operator located in the reactor hall. The operator, positioned on the bridge directly above the core, checked that the experimental device was not stuck before attaching it to a crane to unload it. To do this verification, he lifted the device manually by at most about 10 centimeters. An intense flashlight from the core was suddenly observed, as well as significant water movements without projection and the sound of an explosion was heard. Quickly understanding that an accidental power excursion was occurring, the operator dropped the experimental device, reinserting it into the core. The reinsertion of the device stopped the power excursion. The control rods #2 and #3 (in positions

16 and 34, see Figure 3 below), which had been deliberately left in high position during the operation, fell because the core instrumentation had exceeded the safety thresholds. The operator in the control room thought that the fall of the rods was due to a recurrent power failure. So, he reset the safety chain, thereby erasing all the warning displays. He was then informed about the accidental excursion by a call from the radiation protection service, whose measurement chain indicated that the safety threshold had been exceeded.

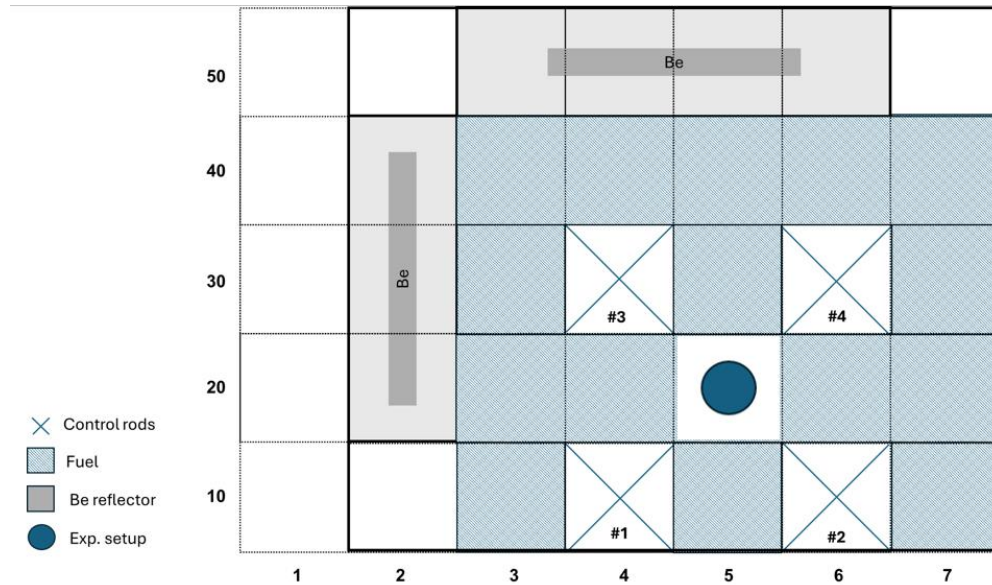


Figure 3. The core configuration before the accident [2]

The power excursion was produced by the partial removal of the highly neutron-absorbing central device. However, several times in past operations, this device had been safely removed from an identical core configuration with both control rods #1 and #4 set in low position. The accident can therefore only be explained by a position error of one or both control rods. This was confirmed after the accident by activity measurements, which showed that the control rods #1 and #4 had been only partially inserted, as both their uranium and cobalt parts had been activated. Figure 4 shows the collimation system used to measure relative gamma activity along a rod and the comparison of the axial activation profile of rod #4 with the profile of a not inserted rod (rod #3). The offset between the activity maxima indicates the offset between the position of rod #4 at the time of the accident and its high position. The activation of the cobalt zone of rod #4 is also shown.

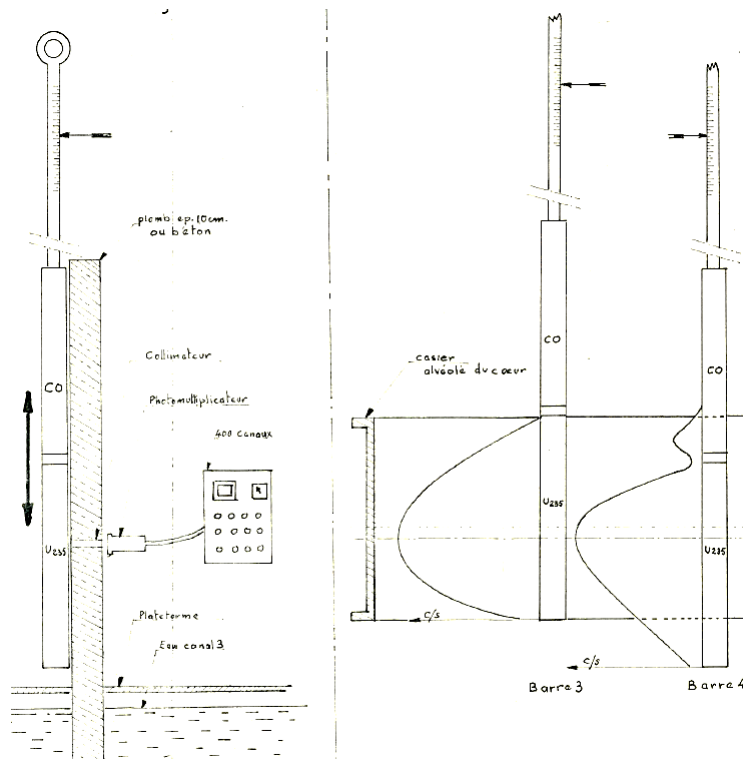


Figure 4. Left: collimation system. Right: activation of both the cobalt and uranium zones of rod #4 (partially inserted), compared with the axial profile of rod #3 (not inserted)

The day after the accident, activity measurements were also carried out on two fuel elements (see Figure 3 above for positions 17 and 27). Based on this measurement, and considering a low fuel irradiation before the accident, the total number of fissions in these fuel elements was determined. The calculations extrapolated to the whole core led to a total number of 6×10^{17} fissions and confirmed that the control rods #1 and #4 were not in the low position when the experimental device was unloaded. This deduction was also confirmed by the linear counting rate recorder, which indirectly indicates the multiplication factor $1/(1-k_{eff})$ applied to the initial flux of a neutron source inserted into the core. This record indicated a neutron flux level before the excursion higher than the usual subcritical level (when all rods are in low position), thus diminishing the margin to criticality. This record also shows that the control rods #1 and #4 fell normally (like rods #2 and #3) after the safety threshold was exceeded.

3.3 Analysis of the accident

About the cause of the accident, the most credible assumption is a bad reading of the position of the control rods, due to faulty lightning in the control room, which was too bright to read displays correctly. Also, even if the control rods were not totally stuck, there was maybe a default in the clamping devices of the rod insertion mechanisms. Previous experience had also shown that the button used to lower the four control rods could be blocked quite easily.

This accident occurred after a unique failure on the control rods position reading. Such situations should no longer occur today in French facilities complying with nuclear criticality safety regulation. Indeed, the loading and unloading operations of reactors shall respect the French safety authority (ASN) decision n°2014-DC-0462. This decision specifies the double contingency principle, that is: a criticality accident should not occur following a unique failure and, if it can occur following two failures, these failures should be independent, each one of low probability and detected within a short period of time to allow intervention.

The decision states that if this principle cannot be applied, the operator must implement technical and organizational measures to make accident scenarios extremely unlikely, with a high degree of confidence.

Among others, the following modifications were added to the facility after the accident:

- the modification of the control room lighting,
- the painting in bright colors of some parts of control rods for better visual identification of their position from the bridge,
- technical improvements of both clamping devices of the rod insertion mechanisms and devices signaling the rod positions (microswitches on the mechanisms, etc.),
- organizational improvements (notably, before any operation on the core, a communication between operators in the reactor room and in the control room, to confirm the position of the control rods as expected).

The water height was sufficient to provide radiological protection, so the consequences of the accident were limited to technical damage. Many fissile elements (uranium and aluminum alloy plates) were deformed and the control rod #1 could not be lifted after the accident.

The issue of the position of the neutron source was also investigated following the criticality accident. It was concluded that the neutron source should have been in such a position that part of the core separated it from the instrumentation. In the ISIS core, this separation was insufficient and, consequently, when the core was far from the critical state, the count rate due to the neutron source was predominant and reactivity variations were relatively unnoticed by the instrumentation. This could be seen on the counting rate recording just before the accident, which showed the influence of the high position of the control rod #1 (counting rate higher than the one observed with all the rods in low position), but no influence of the position of the control rod #4. Under these conditions, the changes made to the core configuration were less noticeable.

4 A THIRD RESEARCH REACTOR - 1971

A French zero reactor, operating since the 1960s, was devoted to the qualification of fuel elements or complete cores (mock-ups or real cores). In 1971, a criticality accident occurred in this reactor. .

4.1 Description of operations

This accident occurred during the final stage of a testing program. This stage consisted of removing experimental neutron absorbing rods (referred to as "experimental rods" in the paper) located in each quadrant of the core (see Figure 5) and inserting in quadrant #1 a cluster of spare absorbers from a prototype reactor (referred to as "prototype rods" in the paper). The prototype cluster was composed of eleven neutron poison rods. The test objective was a check of the cluster anti-reactivity in a well-characterized core.

The procedure, described in the safety report, required the draining of the core water before making any significant change during the core loading. Once water was reduced to a water level to be determined by experimental team, the new core loading could be performed and then a new subcritical approach (progressive increase of the water level) had to be carried out. This procedure also allowed to skip water draining in case of an "insignificant" modification of the core loading.

Two engineers oversaw the reactor and its modification, and these two engineers were assisted by a technical staff. These engineers were very familiar with the reactor core as they were respectively in charge since 1969 and 1970 after having held previous positions in the technical staff in the 1960s. They had a strong collaboration, exchanging their ideas on the experiments progress and tests results several times a day. These engineers used to carry out testing on the prototype reactor and they used to precisely document these tests. But this was not always the case for the tests carried out in the research reactor, for which the

preparation of experiments was sometimes done verbally. This preparation respected the only organizational rule specified in the operating authorization and instructions. Indeed, these rules specified that the tests shall be carried out "under the responsibility and in the effective presence of an operator engineer". During the tests preceding the accident, the required level of water had not been explicitly specified in an operating instruction, but examination of the shift notebook showed that these tests had been carried out under the usual safety conditions with adequate core draining.

4.2 Presentation of the accident

The campaign was carried out under specific conditions: it was the end of a program that included numerous tests within a tight schedule, including some work conducted during the night. The engineers had most probably experienced tiredness and stress. More important, the extraction of the experimental rods and the setup of the prototype rods were carried out ahead of schedule, a decision made by the assistant engineer. He wanted to take advantage of the remaining working time, available materials and personnel to prepare the tests of the prototype rods in advance, which were originally scheduled on the following workday. The engineer in charge of the reactor gave his approval, but had not determined the water level to reach (after draining).

Despite the absence of a real formalized analysis of measurements, several values (critical soluble boron concentrations related to corresponding poison concentrations in experimental rods) were reported in the shift notebook and clearly showed that the experimental rods in place at that time provided about 4,000 pcm anti-reactivity. The experimental rods removing was carried out one by one and sequentially for each quadrant #1 to #4. This operation could be done directly in quadrants #1 and #3, but required, for quadrants #2 and #4, to raise each cluster of safety absorbers temporarily to a height of about 20 cm above the fuel elements. This difference was due to the height of the safety absorbers in quadrants #2 and #4 (120 cm), greater than the height of the control absorbers in quadrant #3 (55 cm). After the removal of the experimental rods, the safety rods were reinserted in the lower position.

The day of the accident, after performing the water drain at a level of 70 mm below the upper end of the fuel elements, engineers performed the operations planned for quadrants #1 to #4. The critical excursion occurred during the removal of the last experimental rod from quadrant #4, while the safety absorbers were raised. This rods configuration is shown in Figure 5 below, right image.

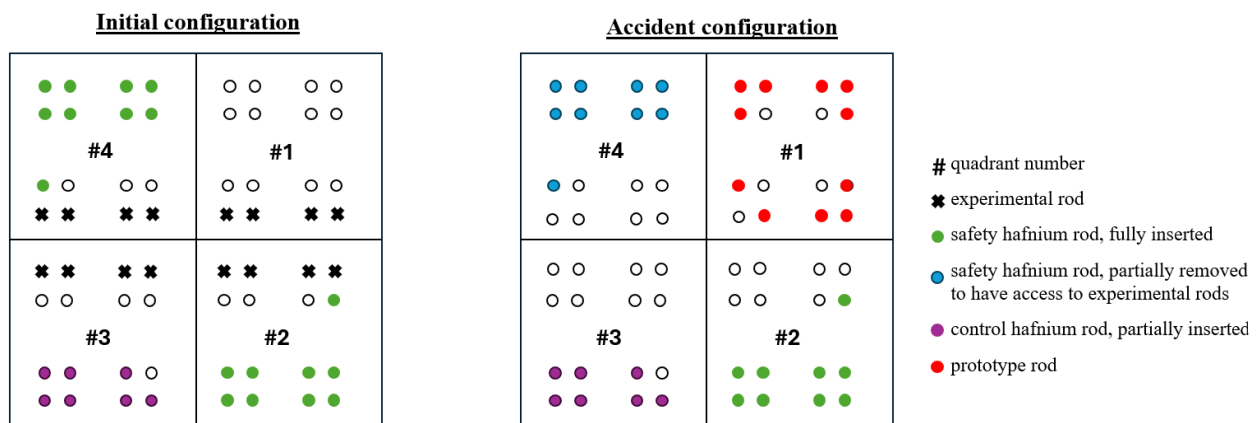


Figure 5. Representation of experimental, safety Hf and prototypes rods before and during the accident (no representation of the fuel)

The gamma radiation led to the triggering of audiovisual signals. The assistant engineer then put the safety absorbers of quadrant #4 back into the reactor, ordered to evacuate the reactor hall, rushed to the control

room to order the fast emptying of the tank, and returned to the reactor hall to insert 1,200 mm poison rods into the available guide tubes.

The evaluation of the radiological doses received was difficult, because after the end of the planned test program (and before deciding to prepare for the subsequent tests with the prototype rods), the assistant engineer was no longer wearing his lab coat fitted with dosimeter films, and the control panel had been cut off. Only the health bay was operational, and its saturation made it impossible to know the maximum dose. Calculations showed a reactivity insertion of about 400 pcm above delayed criticality, leading to an average energy of about 65 J per gram of fuel, confirmed by the measurement of the activity of lanthanum 140 on a rod subjected to an "average" flux. Moreover, examinations showed that the geometric features of the rods had not been altered.

4.3 Analysis of the accident

The accident occurred because of a very insufficient draining (at a level of only 70 mm below the upper end of the fuel elements) prior to the removal of the experimental rods, which was considered to be an insignificant modification. This assumption was not correct because of the small size of the core, the experimental rods provided significant anti-reactivity which was underestimated.

The nuclear utility has identified the following causes and retained the corresponding corrective or preventive actions:

- insufficient preparation of the intervention, probably associated with fatigue at the end of an intensive program. These conditions led to an erroneous statement on the low impact of experimental rods on core reactivity. It was then concluded that emptying core tank followed by a new subcritical approach (as imposed by the instructions for each new loading) were not necessary. To address this point, the operator decided to modify the safety report and instructions to reinforce vigilance when modifying the absorbers, equally as when modifying the fuel elements,
- the absence of measures and means of rapid action that would have made it possible to reduce the irradiation of personnel (in particular, the assistant engineer had to move to the control room to activate the rapid draining). To address this point, the operator decided to install an automatic rapid draining system controlled by the neutron flux in the vicinity of the reactor.

These actions helped improve the operations on the reactor.

The analysis of this accident also reveals a shortcoming in the applicability of procedure allowing for not draining the water in case of an "insignificant" modification of the core loading. Indeed, this lack of measurable values or means to assess what is not "significant", leaving room for the operators' interpretation (an interpretation that may be influenced by external pressures, such as the need to complete actions within a short timeframe). The lessons learned from past accidents highlights the importance of defining clear operational procedures that are easy for operators to use, and specify, that tests are "under the responsibility and in the effective presence of an operator engineer" may not be sufficient to ensure safety.

5 CONCLUSIONS

The critical assemblies of ISIS, ALIZE and the third research reactor were similar, being solid critical assemblies immersed in water. These three experimental devices had in common the objective of carrying out critical experiments, which were still relatively challenging in the 1960s and early 1970s. As with any new discipline, it was necessary to "deal with teething problems", and this is illustrated by the accidents presented in this paper, resulting from errors that may seem "gross" today. They were mainly due to operations carried out too quickly and insufficiently prepared (careless operations and lack of critical

judgment in ALIZE, bad reading of the position of the control rods in ISIS, and early and non-formalized preparation of a test in the third research reactor). They can be seen as criticality accidents because the initial situations were sub-critical, rather than reactivity accidents usually used for an excess of reactivity starting from an initial critical situation.

6 ACKNOWLEDGMENTS

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