Lifetime extension of French 900 MWe NPPs: French TSO main conclusions regarding long term sump performance during a severe accident

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RCCS-2021 – 10##

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ABSTRACT

In the framework of the lifetime extension of the French 900 MWe PWRs beyond 40 operating years, EDF has included, in case of severe accident (SA), a strategy to remove the decay heat from the containment without opening the emergency containment filtered venting system. The new dedicated circuit uses an injection line with a heat exchanger connected to the cold leg of the primary coolant circuit and another feeding the sump of the reactor building and a pump qualified to extreme external hazards conditions and to SA situations.
After the drainage of the refueling water storage tank, water is taken from the containment sump using one of the filtering system implemented at the bottom of the containment. Consequently this filtering system was previously used during the LOCA phase, before reaching the SA phase. A cooling mobile device (ultimate heat sink) is lined on the heat exchanger by the EDF rescue team.
One of the major issues is the clogging of the filtering system due to physical and chemical conditions which can lead to an inadequate net positive suction head margin for the pump during SA and can affect the mechanical integrity of the strainers. Furthermore, despite the filtering system, a part of the debris bypassing the strainers is transported through the dedicated circuit: a second major issue is to ensure that these debris do not damage the pump, degrade the heat exchanger performance or clog other equipment of the circuit.
In addition to the debris released in the sump in case of a LOCA, additional debris created during SA come from the core degradation, the corium-concrete interaction and paints damaged in the containment due to high irradiation.
EDF presented its safety demonstration based on studies and experimental program on strainer clogging. IRSN conducted the safety review of EDF safety case and performed simultaneously one SA test on the VIKTORIA loop in Slovakia.
The paper presents the French background and IRSN conclusions (dated the end of March 2019) on sumps performance issue in case of SA for the 4th periodic safety review of 900MWe PWRs. Some open issues for future R&D are discussed.

KEYWORDS: Long term coolability, severe accident, sump strainers clogging, debris, head losses

1. INTRODUCTION

In the framework of the lifetime extension of the French 900 MWe NPPs beyond 40 operating years, EDF has included, in case of severe accident (SA), a strategy to remove the decay heat from the containment without opening the emergency containment filtered venting system. The new dedicated circuit uses an injection line with a heat exchanger connected to the cold leg of the primary coolant circuit and another feeding the sump of the reactor building and a pump (ND pump) qualified to extreme external hazards conditions and to severe accident situations and backed up by an ultimate emergency diesel.

After the drainage of the RWST (Refueling water storage tank), water is taken from the containment sump in the lower part of the nuclear reactor building using one of the filtering system implemented at the bottom of the containment (called "EASu filter" in the text). Consequently this filtering system was previously used during the LOCA (loss of coolant accident) phase, before reaching the SA phase. A cooling mobile device (ultimate heat sink) is lined on the heat exchanger by the EDF rescue team (Nuclear rapid response force) (**Figure 1**).

During LOCA and SA various debris are generated and carried to the reactor sump water by leaching. These debris constitute the upstream DST (Debris source term). Debris passing through the filtering system constitute the downstream DST when the new dedicated circuit is operating in recirculation mode during SA. The debris loaded water will therefore pass through the ND pump, the heat exchanger, taps, valves and diaphragms, to be reinjected into the primary circuit and into the sump via a zero flow line.

The study of the robustness of the recirculation mode of this new dedicated circuit used during SA requires checking that:

- the upstream DST does not lead to clogging of the filtering system likely to endanger the operation of the ND pump (cavitation risk). This is to ensure that the pressure drop induced by the debris loading of the filtering system does not excessively reduce the margin between the NPSH (Net positive suction head) required and the NPSH available at the suction port of the ND pump;
- the downstream DST in the water is not likely to:
    - endanger the proper operating of the ND pump,
    - significantly degrade the performance of the heat exchanger,
    - cause clogging of other equipment downstream of the filtering system (taps, valves, diaphragms).

EDF presented its safety demonstration based on studies and experimental program on strainer clogging. IRSN conducted the safety review of EDF safety case and performed simultaneously one severe accident test on the VIKTORIA loop in Slovakia.

The paper presents the French background and IRSN conclusions (dated the end of March 2019) on sumps performance issue in case of SA for the 4th periodic safety review of 900 MWe PWRs. Some open issues for future R&D are discussed.

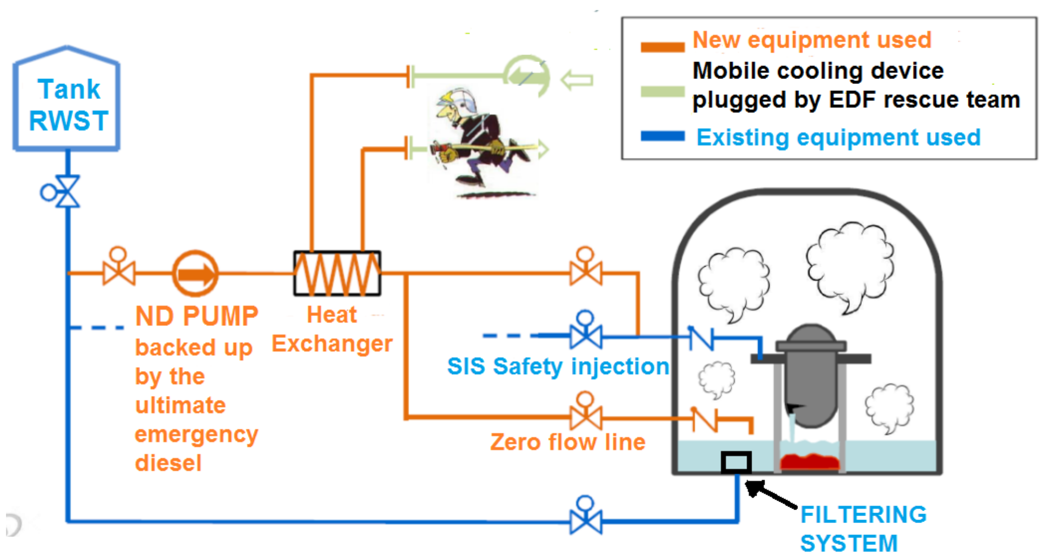

Figure 1 – French 900 MWe PWRs - A sketch of the new dedicated circuit to remove the decay heat from the containment without opening the emergency containment filtered venting system during SA.

2. UPSTREAM DEBRIS SOURCE TERM

In addition to the debris released in the sump in case of LOCA, additional debris created during SA come from aerosols released during the core degradation and deposited into the sump water, fine particles created during the erosion of the reactor concrete basemat by the corium under water and flowing to the sump water, and debris coming from paints damaged in the containment due to high irradiation process during SA.

2.1 Debris released in the sump after a LOCA

The upstream DST is first of all made up of debris generated during LOCA in the ZOD (Zone of destruction) of the primary circuit breach, or outside this zone due to the ambient conditions. On French 900 MWe EDF PWRs, debris from ZOD contains fibers from the destruction of glass wool heat insulators, particulate debris from powdery heat insulator (Microtherm®), paint micro-debris as well as concrete particles. Debris produced outside the ZOD are particulate in nature.

To demonstrate the robustness of the SA recirculation function, the upstream DST was evaluated by EDF on a LOCA. The size of the breach was chosen on the basis of probabilistic assessments. This breach size is smaller than the size of the LOCA breaches chosen on the basis of deterministic assessments and used to demonstrate the robustness of the design basis accident recirculation function [1]. Consequently, a reduction factor, based on the ratio of the volume of insulation destroyed in the ZOD, is applied to the mass of fibers used in the DST for DBA recirculation assessment to estimate the mass of fibers used in the DST for the SA recirculation assessment. In its review, IRSN noticed that the upstream DST currently proposed for SA exhibited consequently a low mass of fibers (the quantity of fibers has an impact on the pressure drop at the filter and on the downstream DST).

Moreover, it was underlined that possible source of additional debris insulation from specific SA phenomena should be investigated such as the damage of primary circuit insulation by thermal shock induced at containment internal spray actuation or by hydrogen deflagration.

A consolidation by EDF of the fibers inventory of the DST used for recirculation under DBA and the DST used for recirculation under SA is on-going and an impact analysis will be carried out thereafter.

2.2 Debris released in the sump during SA

2.2.1 Debris from core degradation

These debris are aerosols released during the core degradation in the containment atmosphere and deposited into the sump water. The mass of these debris is obtained as follows: (masses of fission products and structural materials initially present in the core) × (emission rate of fission products and structural materials) × (possible non-solubility of the fission products) × (fraction of the debris leached to the sumps). Regarding the particle size of these debris, it is considered that the fission products and the structural materials can be assimilated to aerosols of 5 microns and of density 5. These two minimized parameters favor the transport of debris.

Taking into account the current state of knowledge, IRSN deemed acceptable such values.

2.2.2 Debris from concrete erosion

One has to note that the core concrete interaction is limited because the corium, once flooded, will freeze after a while with the greater corium spreading surface allowed, after vessel failure, with the modifications performed in the framework of the lifetime extension of the French 900 MWe NPPs beyond 40 operating years. The debris from concrete erosion considered in the DST are particles created during the erosion of the concrete basemat by the corium under water that are fine enough to flow to the sump water. Above a particle size of 100 µm (density 2.3), it is considered that the concrete debris settles in a few hours and are not considered in the DST.

Taking into account the current state of knowledge, IRSN deemed acceptable such values.

2.2.3 Debris from damaged paints

These debris come from the paints damaged in the containment due to high irradiation process during SA. Data used for the French 900 MWe PWRs come from the results of test campaigns performed under LOCA and SA conditions for the Flamanville EPR painting systems. As a matter of fact, the structure and nature of the paint systems qualified for the French 900 MWe PWRs and the Flamanville EPR are relatively similar.

It is assumed that paint chips of maximum size 10 mm^2 (size > 100 µm, density 1.6) are produced by damaging 10% of all thin painted surfaces in the containment. It is also assumed that the entire 3rd coat of all painted surfaces with thin coatings generate particulate micro-debris (size between 20 µm and 50 µm). Moreover, the painted surface with thin coatings value used to obtain the debris masses is the one from Flamanville EPR, i.e. a surface 1.9 greater than the French 900 MWe PWRs one.

IRSN deemed acceptable such values, taking into account the conservative choice of the value of the painted surface with thin coatings.

3. DEBRIS LOADING OF THE FILTER

In the event of excessive clogging of the "EASu filter", the pressure drop achieved may lead to an insufficient NPSH margin and therefore cause cavitation of the ND pump, which may impair its ability to circulate a suitable water flow in the circuit and therefore to prevent removing the decay heat from the containment without opening the emergency containment filtered venting system during SA. Consequently the safety case is supported by qualification tests to estimate the debris loading of the filter during recirculation in case of SA.

During the review, IRSN underlined that the qualification tests carried out by EDF and using the DST defined previously, mainly "cold" tests, were not sufficient and should be supplemented by "hot" tests representative of SA conditions. These tests should consider all phenomena that could impact the chemistry of the sump water, including soda or boron addition and therefore should be performed simulating the sump water temperature history during SA. For instance, radiolysis is the decomposition of matter by radiation whose energy is greater than the dissociation energies of chemical bonds (ionizing radiation). In the reactor containment, during SA, the γ and β rays emitted by the fission products are likely to interact with the gases in the containment atmosphere and the materials (electric cables) contained in the reactor building and lead to the production of acid species, such as HNO_3 by air radiolysis or HCl if the electric cables are made of chlorinated compounds. Moreover, CO_2 gas is released into the containment atmosphere during core-concrete interaction, particularly if the basemat concrete is a limestone-common sand one. One should investigate the need to take into account or not in the tests such products that may be dissolved in the sump water during SA.

Furthermore, IRSN noted that the qualification tests were all carried out considering a recirculation flow rate corresponding to the pump used during SA recirculation. This state corresponds to a LOCA leading directly to SA. After a LOCA, before entering SA, there may be a possible operation of the ECCS (Emergency core cooling system) and CCS (Containment cooling system) by spray before their failure. In the framework of the lifetime extension of the French 900 MWe NPPs beyond 40 operating years, the pump used during SA recirculation is the ND pump. The ND pump flow rate is 3 to 4 times lower compared to the total flow rate of the ECCS and CCS pumps. This low flow rate in SA conditions increases sedimentation of debris upstream of the filter compared to recirculation during DBA. Consequently, the ECCS / CCS pre-operation before ND pump actuation should be taken into account in the "hot" tests representative of SA conditions.

EDF will perform, before the end of 2022, long-term SA filtration experiments taking into account sump water temperature profile, representative water chemistry and ECCS / CCS pre-operation before ND pump actuation. Such tests will be performed for all the different kind of filters used on French 900 MWe PWRs. The granulometry of the debris downstream of the filter will be analyzed. Such data is needed to evaluate the downstream DST.

4. SEVERE ACCIDENT SCOPING TEST ON THE VIKTORIA LOOP

In the past, IRSN and VUEZ have carried out a large experimental and laboratory program in the open field related to the sump clogging issue. The purpose of this program was to evaluate the impact of possible chemical effects of the circulated solution on leached products generated during a LOCA inside the containment of nuclear power plants. As a matter of fact, temperature and pH conditions of the recirculating sump water, associated with the presence of soda and boron in this water, can generate "chemical effects" with the debris contained in the water. These chemical effects could materialized by the formation of gels / precipitates on the filter within the fibrous bed and could have an impact of the filter head loss. As a result of this investigation, a new test facility was built up: the VIKTORIA loop inaugurated in December 2011 (**Figure 2**) [2].

In 2017, IRSN and VUEZ started discussions related to test plan using VIKTORIA loop to study recirculation process during SA progression taking into account the temperature, composition and pH of the sump water during a SA, to obtain data on head loss evolution of the strainer.

This test, performed in July 2018, simulated a SA following a primary break on a French 900 MWe PWR (breach diameter: 12"). Temperature and chemical addition of species (NaOH, boric acid…) were representatives of the sump circulating fluid conditions during SA.

The maximal value of temperature obtained on VIKTORIA loop is close to 80°C. In the reactor case, the sump temperature during DBA and SA is higher than 80°C at the beginning of the accident. Empirical Arrhenius law provides a rough approximation of the effect temperature has on general reaction rates. This approximation is that the rate of reaction doubles for every 10 °C increase in temperature. This is applied to estimate the sump water temperature history for the test.

The upstream DST was the one previously presented. The filter was a "pocket" filter (**Figure 3**). The scale ratio to define the scaled quantity of debris is equal to 250 for the VIKTORIA test facility.

Figure 2 – VIKTORIA loop facility and view of the strainer mock-up.

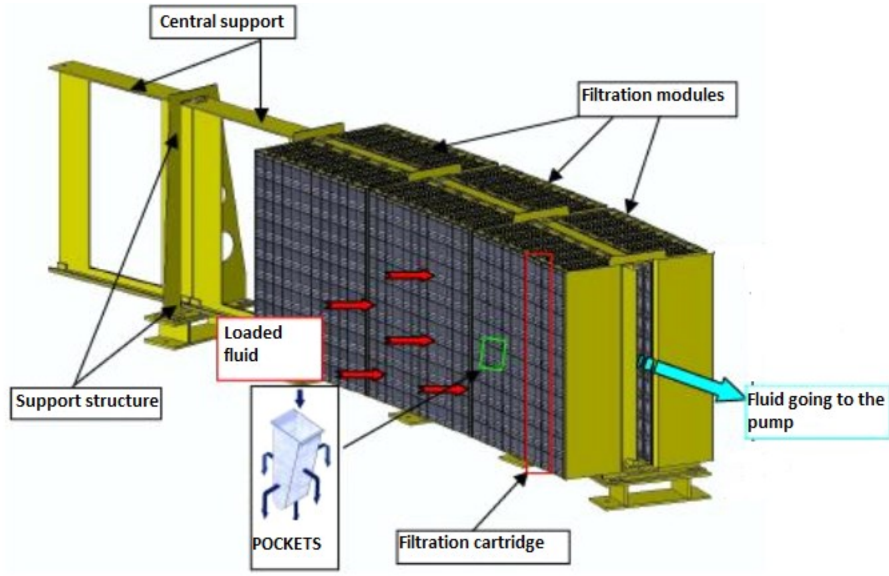

Figure 3 – Pocket filter (CCI trade) used on some French 900 MWe PWRs.

4.1 Chronology of the VIKTORIA SA test

In the accident scenario, from time 0 to 3 h after the LOCA event, one file ECCS and one file CSS are in operation during water injection phase and then beginning of sump water recirculation. In the test, the DST generated during LOCA in the ZOD, or outside this zone due to the ambient conditions, is injected. Injection of debris was performed by 16 equivalent and successive batches.

In the accident scenario, from time 3 h to 26 h after the LOCA event there is no water recirculation (ECCS and CSS are assumed to fail 3 h after the LOCA event). Core melt will consequently occurs. To simulate this phase in the test, the circulating fluid flow is rearranged to bypass the main strainer and maintain a required temperature.

In the accident scenario, at time 26 h after the LOCA event, the EDF rescue team is assumed to activate the ND pump of the dedicated system to remove the decay heat from the containment without opening the emergency containment filtered venting system. Sump water recirculation starts again using low flow ND pump. In the test, SA debris are injected. The SA debris injection was split to 4 equivalent parts and injected within 4 day.

4.2 Main findings of the VIKTORIA SA test

During the phase simulating ECCS / CCS pre-operation before ND pump actuation, the final head loss at the filter after the stabilisation was low: 2 kPa (0.2 mCE).

When the recirculation was reactivated, the head loss was negligible and the flow rate was not enough to recreate a compact fiber bed. The interrupted water circulation linked with the stopping of the ECCS / CCS destroyed the compact fiber bed on the filter.

To end the test, the loop was cooled down progressively to 60°C and later to 40°C. During these phases, no measurable head loss was observed.

The main findings can be summarized as follows:

1. The interrupted water circulation linked with the stopping of the ECCS / CCS destroyed the compact fiber bed on the filter, and the actuation of later SA recirculation simulating the flow rate of ND pump was not sufficient to recreate a fiber bed. Therefore, the measured head loss was negligible.
2. The downstream debris after the actuation of recirculation contained mainly particulates.
3. The fiber bed was very compact due to the large amount of additional particulate debris. The presence of water glass was assumed due to the Na identified using Scanning Electron Microscope with Energy Dispersive X-Ray. Nevertheless, it was not obvious to conclude that a large quantity of water glass was created and able to increase after a long stay at high temperature and to lead to a critical head loss at strainer.
4. The dissolution of debris was identified by rising concentration of various elements.

This pilot test confirmed the VIKTORIA loop ability to perform these type of experiments.

Warning

One should not draw firm conclusions from these scoping test results because of the reservations about the "fibers" component of the upstream DST taken into account and simulated into this test (see chapter 2.1) and also to investigate open issues presented next chapter.

5. OPEN ISSUES FOR FUTURE R&D

Temperature and pH conditions of the recirculating sump water, associated with the presence in this water of soda and boron and eventually other species (nitric acid…), presence of non-negligible masses of metallic material in the reactor (such as zinc, aluminum) leached by basic recirculated sump water, may generate loading on the filter due to "chemical effects".

As a matter of fact, these chemical effects are materialized by the formation of gels / precipitates on the filter within a fibrous bed. The formation of these gels / precipitates is particularly problematic because they can reduce the porosity of the fibrous bed and thus lead to an increase in the pressure drop across the filter. For instance, glass wool heat insulators and Microtherm® can corrode in a soda-basic medium at a high rate under the effect of temperature to release silica, calcium in solution and so on. These mineral species can, under certain conditions, form precipitates / gels on the filter whose composition and structure strongly depend on the chemical composition of the solution including the effect of the buffer.

In order to understand the results of "integral" "hot" tests, such as long-term SA filtration experiments taking into account sump water temperature profile and representative water chemistry, there is a need by means of separate analytical effects tests to better understand the different mechanisms associated to chemical effect as function of the sump water temperature, pH and debris composition. First works are on-going at IRSN on this subject in the framework of a PhD thesis in the frame of DBA accident [3]. For that specific devices are available at IRSN/Cadarache. The first is the COPIN experimental loop, as shown in Figure 4, to perform parametric tests to study impact of water chemistry on head loss. One advantage of this loop of about 100 L is that the temperature can reach up to 110°C, temperature representative of SA conditions. pH, turbidity measurements can be performed as well as elements in solution and surfaces analyses of potential precipitates formed. A second experimental device is a γ-irradiation allowing to simulate radiolysis of water and gas atmosphere in a vessel of about 5 L. The idea as all the tests at large scale cannot be carried out under radiation, is to check if any phenomena induced by radiolysis can alter results.

Among the open issues in SA conditions (not including the debris inventory), we can cite:

- behavior of glass fibers in irradiated solution (rate of dissolution, degradation …);
- role of metallic aerosol coming from the core and being settled in the sump. Soluble aerosol can formed metallic cation which can contribute to form precipitates whereas non soluble aerosol behaves roughly as inert particle which could be partially transported towards the sump filters;
- If some precipitates are formed, are they amorphous or crystalline forms? Are they stable following pH conditions or radiolysis?
- what is the evolution of the pH under SA conditions?

To sum-up, additional tests may be required to evaluate the chemical effect in severe accident conditions.

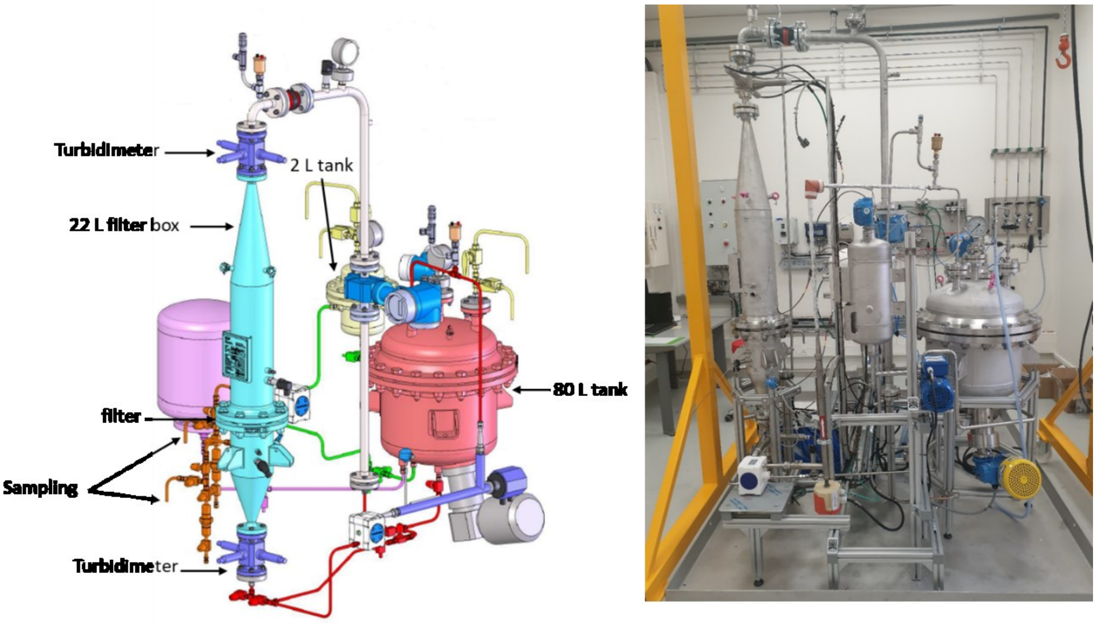

Figure 4 – Schematic diagram and photo of the **COPIN** filter loop

Figure 5 – EPICUR facility to make γ-irradiation of ~4L liquid solution

6. CONCLUSIONS

Reservations were expressed about the "fibers" component of the upstream DST provided in 2019 regarding the SA recirculation issue in the framework of the 4th periodic safety review of 900 MWe PWRs. A consolidation by EDF of the fibers inventory of the DST used for recirculation under DBA and the DST used for recirculation under SA is on-going and an impact analysis will be carried out thereafter.

Qualification tests to estimate the debris loading of the filter during recirculation in case of SA carried out by EDF and using the DST defined previously, mainly “cold” tests, were not sufficient and should be supplemented by "hot" tests representative of severe accident conditions. EDF will perform, before the end of 2022, long-term SA filtration experiments taking into account sump water temperature profile, representative water chemistry and ECCS / CCS pre-operation before ND pump actuation. Such tests will be performed for all the different kind of filters used on French 900 MWe PWRs. The granulometry of the debris downstream of the filter will be analyzed. Such data is needed to evaluate the downstream DST.

In order to understand the results of such “hot” tests, there is a need by means of separate analytical effects tests to better understand the different mechanisms associated to chemical effect as function of the sump water temperature, pH, debris composition and potentially radiation effects. First works are on-going at IRSN on this subject in the framework of a PhD thesis. This could be considered as an open issue for future R&D.

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