Viktoria experiments investigating the filtering system in the sump of a pwr after a loss of coolant accident : Part I Physical /chemical effects on strainer head loss evolution

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ABSTRACT

During a Loss Of Coolant Accident, water is injected by the Emergency Core Cooling System (ECCS) to ensure the long-term core coolability and by the Containment Spray System (CSS) to remove residual heat and to maintain containment integrity. 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. A filtering system is implemented at the bottom of the containment to collect debris produced by the pipe break as well as other latent materials, such as fiberglass, paint and concrete particles, and to minimize the amount of debris entering in the ECCS and CSS systems. Consequently, one of the major issues to be assessed is the plugging of the filtering system due to physical and chemical conditions which can lead to an inadequate net positive suction head (NPSH) margin for the ECCS and CSS pumps and can affect the mechanical integrity of the strainers. The “Institut de Radioprotection et de Sûreté Nucléaire” has launched an experimental R&D project investigating the possible plugging of the sump filter by integral tests performed in the VIKTORIA loop.

The analyses of the experiments give very useful results regarding sedimentation, transport of debris and physical plugging, as well as the impact of chemical effects on strainer head loss evolution.

KEYWORDS

Long term coolability, sump filtering, debris, head losses

1. INTRODUCTION

- The filtration of the water of the sump is one of the major issues to ensure the long term core coolability after a Loss Of Coolant Accident. From 2001, the “Institut de Radioprotection et de Sûreté Nucléaire” has launched an experimental R&D project investigating the plugging (by physical and chemical effects) of the strainer and the downstream effects. Later, after several programs in different test facilities (IVANA, MANON, ELISA), the need for integral experiments was raised. For this purpose, the VIKTORIA loop, co-funded by IRSN and VUEZ and operated by VUEZ at Levice in Slovakia was constructed in 2011.

The objectives of a recent experimental program performed in the VIKTORIA, in operation since 2012 are:

- To collect data concerning the transport and settling of the debris in the reactor sump with an approved upstream debris source term;
- To investigate the head loss of the strainer (physical plugging) by studying the behaviour of the strainer for different kind of debris source term and relevant thermal hydraulic conditions (water temperature and flow velocity on the strainer surface);
- To investigate the long term evolution of the head losses (at least for 30 days) in compliance with the temperature profile (estimated by IRSN) and the chemistry of the water solution in the sump during a typical LOCA transient.

For this project, the VIKTORIA loop was equipped with one of the strainers (at reduced scale) provided for French NPPs.

2. CONTEXT AND PHENOMENOLOGY

After the incident which occurred at Barsebäck (Sweden) nuclear power plant in 1992 [1] which pointed out the risk of strainers clogging by debris generated by a LOCA, various actions were launched by utilities, research organisations, regulators and TSOs in several countries to investigate this clogging issue. In particular for pressurized water reactors (PWRs), several research and development works [2] were carried out to assess the impacts of such debris on the safety systems used in LOCA accidents during the phase where these systems take suction through strainers from the sumps located at the bottom of the containment building.
After a Loss Of Coolant Accident (LOCA), water is injected into the core by the emergency core cooling system (ECCS) to insure the long term core coolability. The containment spray system (CSS) is used to remove the residual heat from the containment and to maintain the containment integrity. At the beginning of the accident, ECCS and CSS pumps take suction from the RWST. As soon as a low water level is reached inside this tank, these pumps are switched to a "recirculation mode", the water is then injected into the core and to the CSS spray nozzles sucking water in the sumps located on the lower part of the reactor, fed by the water running down from the break site and the CSS nozzles (cf Fig. 1 from [3]).

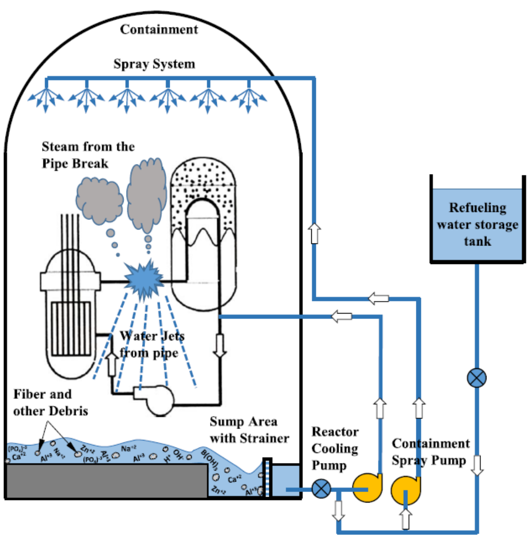


Fig. 2 a) Fig.2 b)

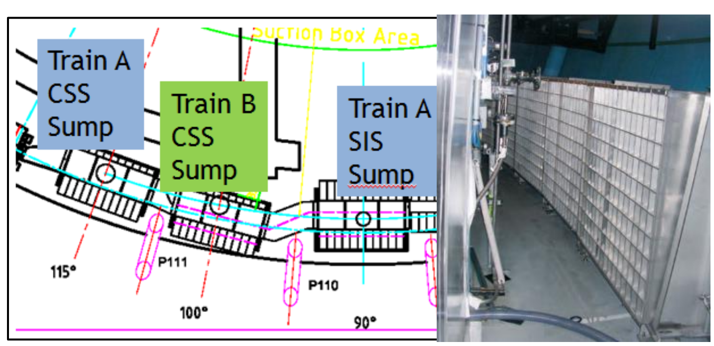


Figure 1. (left) Simplified scheme of the recirculation loop in the pressurized water reactor

Figure 2. (right) Upper view of the containment building annular zone of the 900 MWe series.

The sumps at the bottom of the reactor building are fitted with a strainer system in order to minimize the amount of post-LOCA-generated-debris entering the ECCS and CSS lines which could impede their safety functions. The primary break could generate shock waves and jets of coolant. Debris is then produced in the vicinity of the break. Debris could also result from the evolution of ambient conditions inside the reactor building due to the break and from the sprayed water. This debris consists of a fraction of dislodged insulation materials and other materials such as paint particles and concrete dust.

Smaller and more transportable debris can be carried to the strainers and may create a debris bed. The way the particles are trapped in the strainer bed, or pass through it, depends on their size and properties, and also on the arrival delay from the break time. The fibrous bed also results from mechanical phenomena or chemical reactions under LOCA temperature and pressure conditions. The accumulated debris in the fibrous bed on the strainers may increase the pressure drop across them and thus decrease the net positive suction head (NPSH) margin available for the ECCS and CSS pumps. It can result in cavitation and failure of the recirculation function. Moreover all the ECCS and CSS components located downstream the strainers must be qualified with water containing debris that could pass through the strainers.

The availability of ECCS and CSS safety functions in case of post-LOCA-generated debris is one of the major safety issues to be more deeply investigated and verified. IRSN has carried out recent investigations to obtain reliable justifications related to the demonstration of this operation mode, relying on both analytical arguments and experimental results. In order to support its review on the subject, IRSN has launched its own experimental R&D project, using the VIKTORIA facility.

IRSN expertise and its supporting research activities deal with the risk of strainers plugging as well as with the assessment of the impact of the debris on safety equipment located downstream the strainers, including fuel assemblies, and addresses both physical and chemical effects of the debris. Different key issues and parameters are identified : the transport and the settling of the injected debris, the characterization of the upstream debris source term (amount of heat insulation, coating particles elements that could be released by water wash, size and distribution of debris), the maximum head loss and the net positive suction head margin for the ECCS and CSS pumps, the impact of the chemical phenomena (temperature profile, pH, consequences of the strainers clogging), the characterization of the downstream debris source term, qualification of the ECCS and CSS components and core cooling capacity with debris-loaded water.

Strainers are implemented in the annular space in the lower part of the reactor building (cf Fig. 2a). New technologies of different design are now implemented in French Nuclear Power Plants (Fig. 2b).

In case of a break on the primary coolant system, the volume of space affected by the jet of the primary break, or zone-of-influence (ZOI), is modelled to define and characterize the amount of generated debris.

The recommended ZOI is a spherical boundary with its center located at the break site (Fig. 1). The ZOI is defined as the volume around the break in which the fluid escaping from the break has sufficient energy to generate debris from insulation, coatings, and other materials within the zone. The use of a spherical ZOI aims to encompass the effects of jet expansion resulting from impingement of structures and components, truncating the sphere wherever it intersects any structural boundary of large robust equipment. A ZOI is defined for heat insulation; another one for paint particles, based on the recommendations of USNRC to the Nuclear Energy Institute [4]. The amount of concrete particles is based on weathering tests with a water jet under primary circuit conditions.

Latent debris are also considered and correspond to those remaining inside the reactor building after a standard process of cleaning before restarting the reactor and are submitted to the water washing. This latent debris consists of firewall products, and other waste materials. Among the debris generated at the break site, it is accepted (today) by the operator that close to fifty percent of the heat insulator fibrous debris is carried downwards to the strainers. This transport coefficient is based on numerical analyses of the fluid flow generating by a primary break. Moreover, one hundred percent of the coating particles, due to their sizes, are considered carried to the bottom of the reactor building. All the debris accumulated on the containment floor are carried to the strainers. The size distribution of the debris is established from destruction tests with a water jet and under accidentals conditions.

3. DESCRIPTION OF THE FACILITY

Since 2001, IRSN (France) and VUEZ (Slovakia) have performed an extensive research program [5] resulting today in an important amount of data and knowledge especially on the chemical effects issue [6]. This includes the main results of these experimental programs and the lessons learned from test campaigns for French nuclear power plants (NPP), US and Chinese reactors. Nevertheless, some questions remain still opened, in particular the LOCA induced long-term debris effects increasing the head loss of the strainer by chemical precipitation or “downstream effects” on safety equipment, on the main coolant system and fuel assemblies, as a combined action of the temperature and the chemical composition of the solution in the sumps. These issues still need to be addressed and research to be conducted to characterize their importance. The need to consider these more complex effects led to the design of a new and more flexible loop. The new loop called VIKTORIA [7], allows representing more global and relevant characteristics, and will have the capacity to model different layouts of NPPs of generation II and III. The main objectives of the test loop are to study a strainer module taking into account head loss, chemical consequences and downstream effects. This will allow for Safety Authorities, to establish safety requirements to be used for new devices proposed by the utilities and for the utilities, to qualify their new devices with respect to safety requirements recommended by their Safety Authorities.

The VIKTORIA (Fig. 3) thermal hydraulic facility consists of different interconnected segments (Fig. 4):

- Debris preparation tank **(1)** and injection tank **(2)** where the debris, that would be transported to the strainer, is introduced and homogenously mixed;
- Specific material tank **(3)** - a so-called “leaching tank” for placing coupons and samples of representative chemical reactive materials (such as debris) that would not be transferred to the strainer;
- Spray system tank **(4)** for placing coupons and samples of representative chemical reactive materials that would be exposed to containment spray (*not used in the present project*);
- Strainer tank **(6) -** a tank for placing a scaled segment of a strainer. The injection tank **(2)** is connected to the strainer tank by a flume **(5)** to prototypically simulate the debris transport to the strainer;
- External tank **(7) -** a tank for placing a full scale segment of a strainer and retention baskets for EPR configuration: it may be used to increase the amount of water of the overall VIKTORIA loop;
- Downstream modules **(8) -** a series of parallel circuits that can be used to place fuel assembly mock-up, valves, heat exchangers, absolute strainers **(9)**, or other components downstream of the main strainer. For the test, it’s possible to use one line equipped with a module including 289 surrogate fuel rods and anti-debris and mixing grids and one line equipped with a module including 25 surrogate fuel rods ,partly heated, allowing potential nucleation sites for chemical effects creation.

a)  b) 

Figure 3. The VIKTORIA facility (a) and the implementation of the strainer (b)

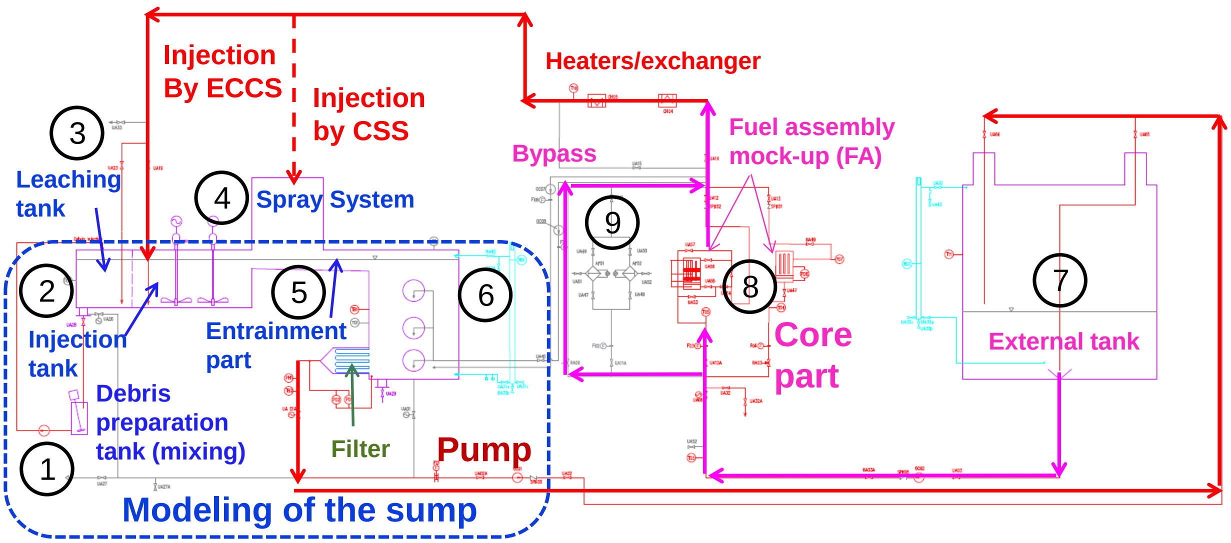


Figure 4. The VIKTORIA loop (circuit) and the position of the strainer

Different types of strainer are implemented in French NPPs, with different geometries: rectangular cartridges, planar and cylindrical grids. The strainer chosen for this study is that using rectangular cartridges: it has been implemented in the VIKTORIA loop in the strainer compartment **(6)** (Fig. 3b) and (Fig. 4).

Table I gives information that has been used to define (on a scale of 1/250) the main thermal hydraulic parameters to perform the experiments.

The scale of the VIKTORIA loop (1/250) versus the nuclear reactor has been defined according the ratio between the total surface available in the reactor sump (526 m^2) and the strainer surface design for the VIKTORIA (2,1 m^2).

Table I. Main characteristics of VIKTORIA with regards to NPP data

Parameter	NPP conditions	VIKTORIA conditions
Sump volume containing debris	1650 m^3	6.6 m^3 (4.2+ 2,4 m^3)
Strainer surface 1 train (2 trains)	526 m^2 (1052 m^2)	2,1 m^2
Flow rate 1 train (2 trains)	2130 m^3/h (3600 m^3/h)	8,52 m^3/h (7,2 m^3/h)
Approach velocity mm/s	1,125 mm/s (0,95 mm/s)	Same

It's very important to respect on one hand the surface ratio and the flow rate ratio, for physical plugging of the strainer, on the other hand the volume ratio with the right amount of water for chemical process between debris and chemical products available in the water, such as boric acid and soda.

4. DESCRIPTION OF THE R&D PROGRAM

4.1. The upstream debris source term

The upstream debris source term (DST), including insulation materials as fiberglass and powder, painting chips and particles, concrete particles and specific products used as firewall protection, is representative of real materials that may be transported to the strainer during the recirculation process. Table II gives the main characteristics of the debris (real materials) and the masses injected in the loop (in brackets the values not transported to the strainer but presents for chemical concerns).

Table II. Type of debris from PWR NPP used during the VIKTORIA experiments

Fiberglass	Insulation powder	Painting debris	Concrete debris	Fire wall products
type A or C	MICROTHERM®	As chips	Class 1 (ø < 100 µm)	MECATISS type
Length : 0,5 mm	(ø < 20 µm)	< 10 mm^2	40 g	100 g
(ø ≈ 8 µm)	800 g	Thickness =	Class 2 (100 <ø< 500 µm)	Ca_2SiO_4 panel
Type B		100-200µm	160 g + (60 g)	100 g
(ø ≈ 5 µm)		1200 g + (600g)	Class 3 (500 <ø< 1000 µm)	Silicon foam
4800 g		As fine powders	165 g	(200 g)
+ (4800 g)		(20 < ø < 50 µm)	Iron oxide	
		710 g	40 g	

Two types of fiberglass insulation were used depending on the test configuration: type A or C and B that differ mainly by their chemical compositions and the diameter of the fiberglass. Real MICROTHERM® and concrete particles, MECATISS fire barrier material (mainly fiberglass and refractory glues) and firewall panel (made of calcium silicate Ca_2SiO_4) were used, as they may have an impact on transport, plugging of the strainer and on chemical effects with regards to their specific chemical compositions. The chemical composition of insulation type A/C and type B was determined by X-ray fluorescence analysis. For tests investigating transport phenomena (Campaign n°1, see §4.4), silicon carbide (SiC) particles were used instead of coating powder, as proposed by PWROG [8] and approved by USNRC/ACRS [9]. The SiC particles and the coating powder ones are characterized by a close settlement velocity.

4.2. The preparation of the debris

Preparation of fibrous debris follows the NEI guide "ZOI Fibrous Debris Preparation" - January 2012 Revision 1 [10]. Batches of fiberglass, manually removed from the conditioning rolls, are placed for 8 hours on a hot plate at 300 °C +/- 40 °C to simulate aging (Fig. 5 (a)). Fiber separation is accomplished a few minutes before the start of the tests and by using a high pressure water jet at 10 MPa during 4 minutes (Fig. 5 (b)). Non-fibrous debris (painting, concrete, MICROTHERM® insulation) are poured in the debris preparation tank (**1**) and mixed together (Fig. 5 (c)) with or without fiberglass before injection in the injection tank of the loop (**2**). Agitators are used in order to avoid debris sedimentation before the transfer of the debris

a) b) c)

Figure 5. Different steps of the debris preparation.

4.3. The injection of the debris in the loop

Debris mode injection is different depending on the kind of debris bed desired on the strainer.

Thick bed tests correspond to tests with a homogeneous injection of the source term of debris. For these tests, equal batches of debris mixture (non-fibrous debris + fiberglass) are injected discontinuously at the beginning of the tests.

We refer to the recommendations of the NEI Generic Guideline for Test Protocol [11] and the know-how of VUEZ to limit the concentration of debris upstream of the strainer:

- Batches of debris injected must not exceed 1/16 of the final theoretical thickness of the fiber bed;
- Time injection interval of debris injected into the test loop must be at least 10 minutes.

So the procedure was precisely:
- Separation of the upstream DST in 16 equal batches for each kind of debris
- Fiber separation with high pressure water jet (one batch
- Addition of non-fibrous debris into the injection tank (one batch);
- Mixing of all the debris in the mixing tank (visual control of the homogeneous mixture) and injection in the loop (one batch);
- Injection of the 16 equal batches every 15 minutes for 4 hours.

The series of tests were conducted according to requirements of the RG 1.82 [12] using conservative assumptions with regards to plugging of the main strainer assuming that the total load of debris arrives to only one available train of ECCS and CSS.

4.4. The test matrix

Four experimental campaigns have been performed in order to investigate:

- The sedimentation / transport phenomena and the physical plugging of the strainer (C1);
- The evolution of head losses taking into account chemical effects (C2);
- The downstream effects: debris source term passing through the strainer (C3);
- And the downstream effect in particular on the head losses of the grids of a fuel assembly (C4).

Table III gives the tests matrix of the VIKTORIA experiments related to the first two campaigns (C1: T1.x tests series and C2: T2.y tests series). The experimental results of the campaign n° 3 (C3) and n°4 (C4) are out of the scope of the paper: they are described in the part II of the paper [13].

Table III. VIKTORIA Experiments - Test matrix

Test n°	DST	Q (m^3/h)/V (mm/s)	Water temperature	Duration
T1.1	Nominal with fibers Type A	8.5 / 1.1	30°C	1 day
T1.2	Nominal with fibers Type A	22.7 / 3	30°C	1 day
T1.4	Nominal with fibers Type B	8.5 / 1.1	30°C	1 day
T1.5	Nominal with fibers Type A	8.5 / 1.1	30°C	1 day
T1.6	Nominal with fibers Type A	8.5 / 1.1	80°C	1 day
T2.1	Particles + Fibers Type A + paints	8.5 / 1.1	80→43°C *	30 days
T2.2	Particles + Fibers Type B + paints	8.5 / 1.1	80→55°C *	6 days
T2.3	Particles + Fibers Type A+ SiC	8.5 / 1.1	80→55°C *	6 days
T2.4	Particles + Fibers Type A+ B + paints	8.5 / 1.1	80→45°C *	15 days

* As the maximum temperature in the VIKTORIA loop is about 80°C (atmospheric pressure design), the peak temperature of the water sump above 80°C is substituted by a temperature plateau at 80 °C during 38 h in order to take into account the kinetics of the potential chemical reactions with the hypothesis that kinetics are doubled each 10°C above 80°C (using Arrhenius law type).

Test **T1.1** is the experiment with nominal parameters to investigate the sedimentation/transport phenomena and the plugging of the strainer which is measured by the pressure drop (1 day test).

Test **T1.2** will give the effect of the flow velocity (1 day test). Test **T1.4** will give the effect of the kind of fiberglass (Type A and Type B used separately). Test **T1.5** is a repetition of the reference **T1.1** (also a scoping test to qualify the behaviour of the loop and to adjust some thermal hydraulics parameters such as the flow velocity in the spreader part which simulate the macroscopic velocity in the reactor sump in front of the strainer. Test **T1.6** will give the effect of the temperature from 30 to 80°C on sedimentation/transport phenomena and head losses (1 day test). This test will give the initial conditions of the test **T2.1** for which the only difference is the addition of chemical products (boric acid and soda) in the water and additional latent debris in the "leaching tank" not being carried to the strainer.
Test **T2.1** is the nominal integral experiment (30 days test) to investigate the chemical effects on the evolution of the head losses, as well as transport/deposition of debris on the strainer.
Test **T2.2** (≈ 6 days test) will give the effect of other kind of fiberglass (type A and type B fiberglass have different chemical composition). Test **T2.3** (≈ 6 days test) will give the effect of surrogate particles replacing the painting powder (may be considered as a short term repetition of **T2.1**). Test **T2.4** (15 days test) will give the effect of the mixture of type A and type B fibers.

For tests of the second campaign, the downstream part of the loop (part 8 on Fig. 4) was supplied with a module representing an element of the lower part of a classical PWR fuel assembly (including lower support plate, anti-debris, spacer grid and one mixing grid). : those results are described in the part II of the paper [13].

5. EXPERIMENTAL RESULTS

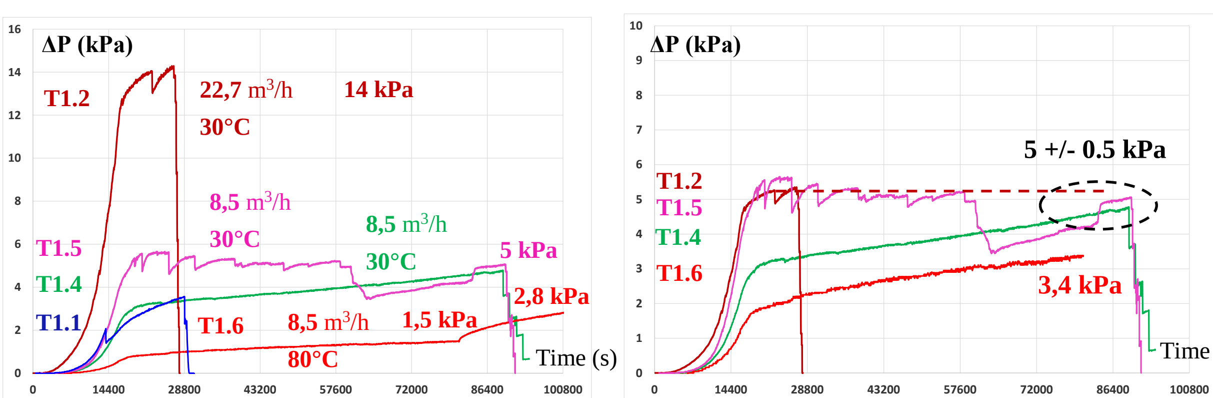
This section gives the experimental results of the VIKTORIA tests performed in 2017, regarding:

- The head loss on the main strainer (physical plugging) for a thick debris bed;
- The competition between sedimentation and transport phenomena in the sump;
- The evolution of head losses on the strainer taking into account chemical effects;
- And the chemical analyses on liquid and debris samples.

5.1. Head losses on the strainer during recirculation

The results of these experiments (C1) for which the issue regarding head losses on the main strainer during recirculation with tap water, are given here after.

Fig. 6a) illustrates the evolution of the head losses on the strainer during roughly 24 hours for various thermal hydraulics conditions (Temperature and flow rate) and two kinds of fibers in the debris source term. The pressure drops range between 1.5 kPa up to 14 kPa (Table IV).



a) Measured values according T/H conditions b) corrected at *8.5 m³/h-30°C*

Figure 6. Head losses on the strainer– Tests T1.1 to T1.6 (campaign C1)

Table IV. VIKTORIA Experiments – Head losses on the strainer

Test n°	Measured head losses (kPa)	Corrected ΔP (kPa)	Mass of Debris collected (g) *
T1.1	3.6 (8.5 m^3/h -30°C)	5.3 (8.5 m^3/h -30°C)	2831
T1.2	14.2 (22.7 m^3/h -30°C)	5.3 (8.5 m^3/h -30°C)	5155
T1.4	4.7 (8.5 m^3/h -30°C)	4.7 (8.5 m^3/h -30°C)	4066
T1.5	5.1 (8.5 m^3/h -30°C)	5.1 (8.5 m^3/h -30°C)	4472
T1.6	1.5 (8.5 m^3/h -80°C)	3.4 (8.5 m^3/h -30°C)	2831
T1.4	4.7 (8.5 m^3/h -30°C)	4.7 (8.5 m^3/h -30°C)	4066
T2.1	7.6 (8.5 m^3/h -55°C) **	11,9 (8.5 m^3/h -30°C)	3616
T2.2	7.0 (8.5 m^3/h -55°C) **	11,0 (8.5 m^3/h -30°C)	3653
T2.3	7.0 (8.5 m^3/h -55°C) **	11,0 (8.5 m^3/h -30°C)	3818
T2.4	8.0 (8.5 m^3/h -55°C)**	14,0 (8.5 m^3/h -30°C)	3861

* ~8,2 kg injected at VIKTORIA scale ** after 3 days for water temperature at 55°C

The head loss across a debris bed could be evaluated with the Ergun correlation [14], characteristic of a particles bed, and including viscous and inertial terms:

$$-\frac{dp}{dz} = h_k \frac{(1-\varepsilon)^2 \mu}{d^2 \varepsilon^3} v + h_\eta \frac{(1-\varepsilon)\rho}{d\varepsilon^3} v^2 \tag{1}$$

with ν the fluid velocity, μ the dynamic viscosity, ρ the density of the fluid, ε the porosity of the debris bed, d the diameter of particles and h_k, h_η empiric coefficients. In the case of the sump strainers study, some correlations were developed, in particular the NUREG one [15], approved by the US-NRC:

$$-\frac{\Delta P}{\Delta L} = \left[a_0 \, S^2 . (1-\varepsilon_m)^{1.5} \left[1 + 57(1-\varepsilon_m)^3\right] \mu \, v + b_0 \, S . \frac{1-\varepsilon_m}{\varepsilon_m^{\ 3}} \rho v^2 \right] \tag{2}$$

which is largely used by the international community in that field to estimate the head losses (ΔP) of a debris layer (ΔL).

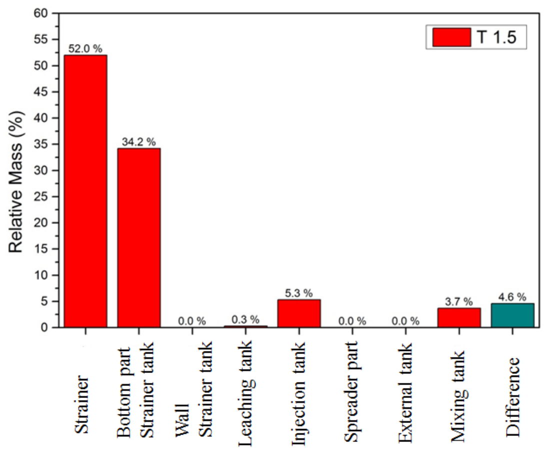
For all tests performed with rather low velocity (1-3 mm/s) and without chemical effects, the inertial term was found to be quite negligible, then the head loss is proportional to the flow velocity and the viscosity of the water (Equ. 1 and 2). So, the evolution of the head losses may be given for the same thermal hydraulics conditions (8.5 m^3/h and 30°C – Table IV- column 3). At the end of the transient (Fig. 6b), head losses were in the range of ~5 +/-0.5 kPa, except for the test T1.6, performed at 80°C for which more settlement of debris is observed leading to less loaded cartridges and therefore lower head losses (~3.5 kPa at 30°C). For this experiment, the temperature of the fluid has been decreased from 80°C to 40 °C (before switching off the pump) lead to an increase of the head losses (Fig. 6a) following strictly the variation of the fluid dynamic viscosity (350 to 650 10^{-6} kg/m/s).

5.2. Transport of debris to the strainer

After each experiment, debris are collected from different parts of the VIKTORIA loop and dried out in order to make the mass balance with the injected debris in the loop to investigate the competition between sedimentation and transport to the main strainer.
Fig. 7 gives an example of the results obtained on the reference test (T1.5) of the first campaign.
Compared to the total mass of injected debris, 52% was transported to the main strainer. For that case, 34% was settled in the lower part of the strainer compartment (painted coating chips and some fiberglass probably mixed with MICROTHERM® insulation powder). Less than 10% of debris, remaining in the injection, “leaching” and mixing tanks, concerns mainly the large particles such as concrete powders (Class 2 and Class 3, ø > 100 µm as sand-like) and chips of painted coatings. Most of the fiberglass and all the fine particles are supposed to be transferred to the strainer and leading to head losses (physical

clogging). Fig. 9 illustrates debris collected on the different (16) cartridges for various selected cases. The most debris-loaded strainer (~5.1 kg) is that of test T1.2 (Fig. 9a) which is due to the highest macroscopic flow velocity upstream the strainer. In that case, settled debris in the strainer compartment is limited to less than 5%.

The average value for tests of the second campaign (performed at higher temperature, leading to slightly a higher settling rate is roughly 3.6 to 3.8 kg (Table 4- column 4), representing 45% of the total injected debris.



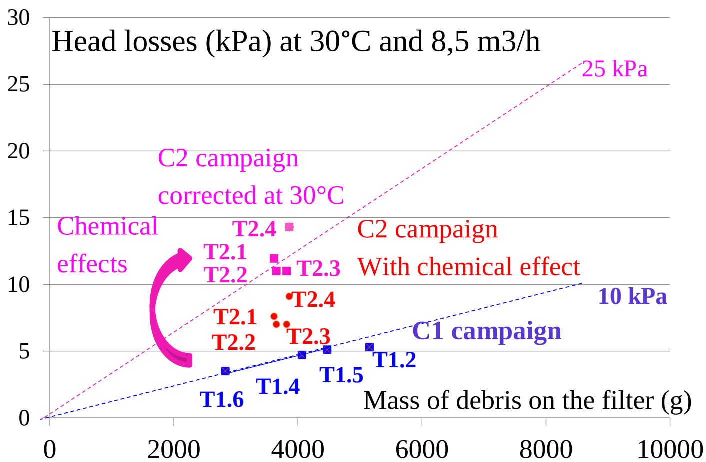


Figure 7. (left) Distribution of the debris in the loop (ex T1.5)

Figure 8. (right) Head losses on the strainer versus mass of debris

With the experimental data of different head losses and the total mass of debris collected on the strainer, it was easy to obtain a correlation between the head loss and the mass of debris transferred to the strainer (Fig. 8). This correlation, which appears linear (blue plots), might be used to extrapolate the final head losses without taking into account the debris settlement observed in the VIKTORIA loop. The available Net Positive Suction Head margin could be lowered with the chemical effects (see § 5.3).
The debris collected in the different cartridges are rather well distributed (less than +/- 10%), what means clearly the homogeneous flow velocities upstream the strainer (the case in the reactor sump).

a) T1.2 b) T1.5 c) T2.2 d) T2.3

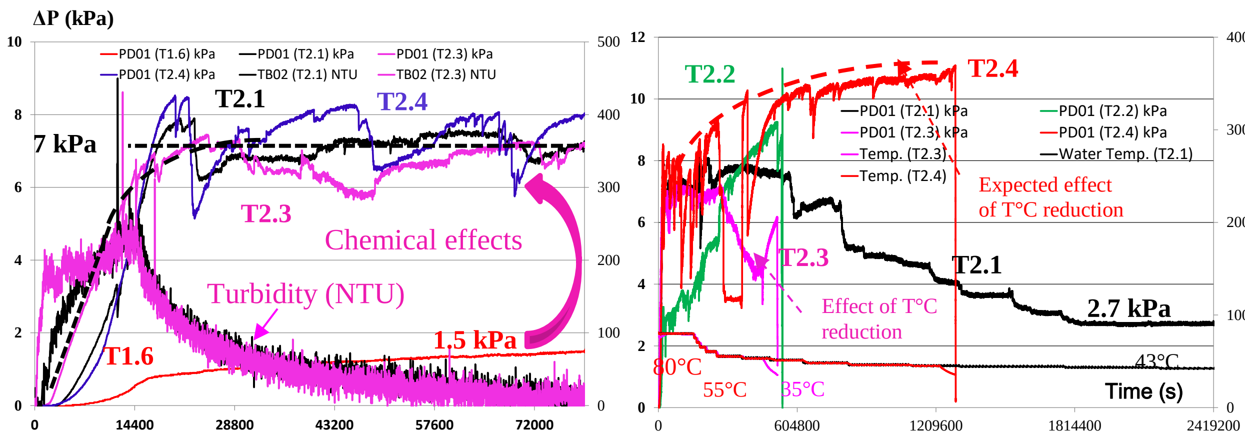
Figure 9. Debris in the cartridges of the strainer for different selected tests

5.3. Evolution of the head losses on the strainer during "chemical" tests

At the beginning of these tests, before debris injection, boric acid was added to obtain a total boron mass concentration of about 2500 ppm in the circulating fluid. NaOH (concentration 1800 ppm, purity 100%) was also added in the solution in order to reproduce the buffered cooling water representative during the post LOCA transient.

Fig. 10 gives the evolution of head losses for tests T2.1 and T2.3 during the first 24 hours (temperature plateau 80°C) compared to test T1.6 without chemical products in the water unlike C2 tests. The tests T2.1 and T2.3 differ in the use of coating powder in one case (T2.1) and silicon carbide surrogates in the other case (T2.3). The general trend of the head losses (T2.1 and T2.3) with a short term stabilization of around 7 kPa, confirm the negligible effect of painting coatings powder compared to SiC surrogates used for the other tests. The strong difference between the head losses for T2.1 and T2.3 tests and the final head losses for T1.6 (≈ 1,5 kPa) seems to be due to the addition of chemical products in the water solution. Evolutions of the turbidity clearly indicate a more efficient filtration in the case of T2.1 and T2.3 tests compared to T1.6 which has a direct consequence on the head losses on the main strainer.

Test T2.2, which differs from the others, only by the type of fiberglass (type B instead of type A) reveals different behaviors at short term, nevertheless after 3 days, the head losses reach the same value roughly around 7 kPa (at 55°C – Table IV). Those values are corrected to take into account the viscosity from 55 to 30°C (Table IV) and reported on the diagram (Fig. 8) which indicates the head losses versus the debris mass collected on the strainer. Comparing those values to that obtained during the first campaign (at 30°C), we clearly outline an increase of the strainer head losses (up to11-14 kPa values measured during the C2 campaign at 55°C and corrected at 30°C) that could be explained by the chemical effects.



a) Tests T1.6 (1 day) - T2.1/T2.3/T2.4 b) tests T2.1, T2.2, T2.3 and T2.4 (28 days)

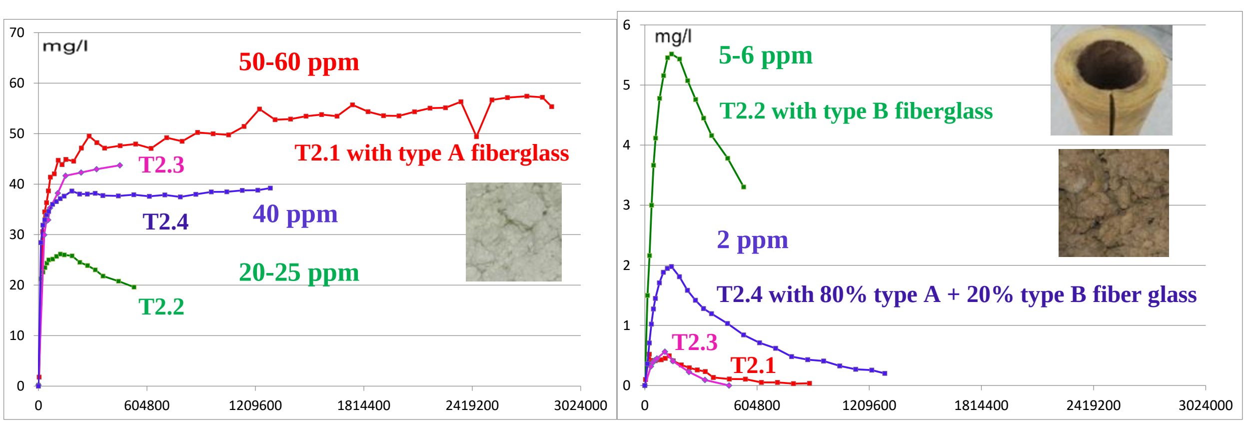
Figure 10. Evolution of the head losses (kPa) on the strainer

The final head losses (≈25 kPa - Fig. 8) extrapolated at 30°C and without taking into account the debris settlement observed in the VIKTORIA loop, would reduce the margins regarding the Net Positive Suction Head (NPSH) for the ECCS and CSS pumps during the recirculation process. At least, increase of head loss due to the decreases of temperature was expected (Fig. 10b– red dash line) but this was not observed during long term experiments. The first decrease of head losses occurred, after 3/6 days (for T2.3 / T2.1) and then after 8 days, different and repetitive decreases were observed for T2.1 (black curve). Final value was close to 2.7 kPa, which could be explained by displacements of the debris inside the cartridges creating a permanent bypass in the strainer.

So, in order to confirm the long term behavior of the head losses (positive effect for safety concern), an additional test (*15 days was enough*) has been performed. As the fiberglass type A and type B materials seem to behave slight differently (Fig. 10b), this long-term additional experiment has been done with a proportion of the two types of fiberglass (roughly 80% A + 20% B in mass) with a ratio that could be observed for the reactor case. The results regarding the strainer head losses clearly indicate head losses up to 11 kPa, value consistent with the temperature decrease and so the loss of pressure drop observed during some tests (T2.1 mainly) cannot be valued.

5.4. Chemical analyses on liquid and debris samples during "chemical" tests

The solution chemistry was followed during the tests from samples of circulating fluid. Fluid samples were analyzed for various elements (K, Al, Mg, Ca, Fe, Si, Mn, Ti), using AES ICP spectroscopy.
The initial solution of circulating fluid contained 2500 ppm of boron (injected as boric acid) and 1800 ppm of sodium hydroxide. This combination creates a buffered solution with large buffering capability what is proved by the stabile pH value over the each test (ranging between 8 and 8.5). Fig. 11 illustrates the silicon and aluminum concentration (as an example), which clearly indicates corrosion of the fiberglass.
Tests T2.1 and T2.3 show approximately the same behavior. Test T2.2 can be clearly identified due to the different chemical compositions of the fiberglass. These results are consistent with the chemical composition of the fiberglass. The most representative is a concentration of Si and Al because the initial insulation composition. The concentration of all elements increases intensively at the beginning of the tests. After approximately 2/3 days when the solution became oversaturated for various elements the back-precipitation may be observed with the decreasing concentration of Al and Si. The test T2.4, performed with a mixture of type A and type B fibers gives consistent results with intermediate concentration of Si or Al contents.



a) Silicium b) Aluminium

Figure 11. Measured silicon and aluminum concentration during chemical tests

The main component for both tested types of insulation (type A and type B) is SiO_2. However type B (mainly used for pipes insulation) has approximately 25w.% less amount of SiO_2. Silicate oxide is replaced by Al_2O_3 which is significantly higher in type B insulation (~ 20 w.% versus less than 2 w.% in type A). Both types of fibers contain alkalis (Na_2O, K_2O, CaO and MgO). The mass of individual alkalis is presented differently but their total amount is ~ 27-28 wt %. Fibers type B contain ~6 wt % more Fe_2O_3 when fibers type A contain only ~ 0.5 wt %. This is clearly observed in the measurement of Iron contents.
Numerous samples taken in the cartridges of the strainer were analyzed by SEM/EDS (Fig. 12): most of the fiberglass seems to be mixed with chemical compounds including NaOH and SiO_2 (Fig. 12a) and b)). The deposited fiberglass (Fig. 12) can be divided into the thick diameter (~10 µm) and thin or very thin diameter (~1-2 µm). The chemical composition of fiberglass is close to the composition of the pure glass.

High contents of Na, Si and O_2 were noted in the composition of the assessed dried samples of fiber bed deposited on the strainer. Sodium silicate (such as Na_2SiO_3) which is an alkaline layer could be created from the interaction of the silicon oxide (dissolution of fiberglass) and sodium hydroxide (NaOH) present in the water and or by fiber corrosion (including Na_2O) , by the following chemical reaction :

$$2NaOH + SiO_2 \rightarrow Na_2SiO_3 + H_2O \qquad (3)$$

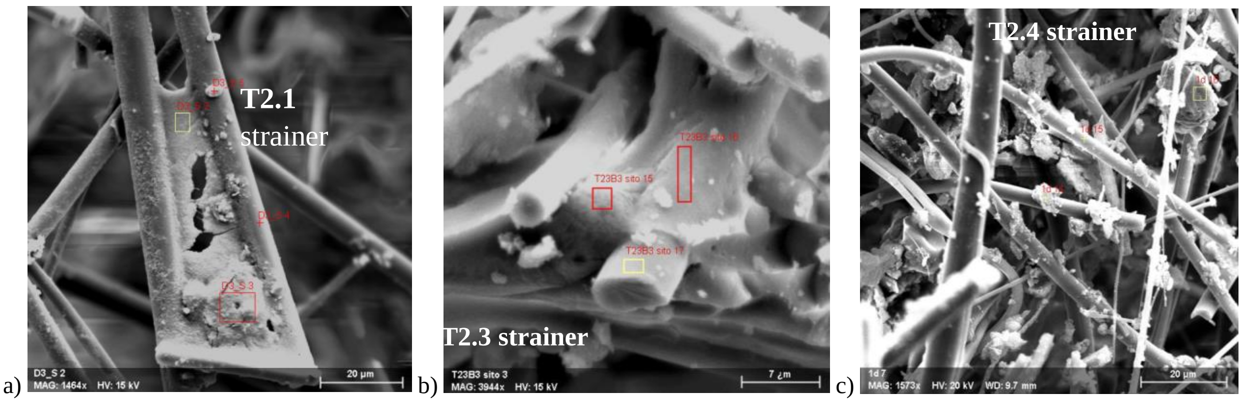


Figure 12. SEM/EDS [1] measurements – precipitates created on debris samples

This creation of a sticky form could contribute to the quick increase of head loss by the decrease of the bed porosity thus more effective to capture the debris. It means that the glass has an extremely low chemical resistance against to the circulation fluid composition at high temperature and can create this very thin and sticky layer in a very short delay. Others chemical components (Aluminum silicate such as $NaAlSi_3O_8$) could also be created, by the presence of aluminum in the insulation materials, and enhance the observed phenomena [16]. Calcium provided form corrosion of fibers and concrete may also form precipitates such as $Ca_2B_2O_5$, $Ca_3(BO_3)_3$ due to the presence of boric acid in the buffered water. All those elements are found by the SEM/EDS measurements depending on the locations.
The presence of MICROTHERM® insulation powder carried to the strainer (increasing the head loss) is proved by the high content of TiO_2 (10 to 50%) depending of the location in the samples. In addition to SiO_2 (~60 wt %), MICROTHERM® includes also 37% of TiO_2 and few % of alumina (Al_2O_3). Paint particulates (or SiC surrogates) were carried to the strainer, this could also increase the head losses. This was also proved by the presence of carbon in the debris bed samples.

6. CONCLUSIONS

The analyses of the experiments on the VIKTORIA loop give very useful results regarding:

- The competition between sedimentation and transport to the strainer;
- The formation of the debris bed on the strainer and its stability;
- The impact of temperature and chemical effects on pressure drop evolution.

The tests highlight the settling of the largest particles (concrete and painted coatings) and part of the fiberglass, the transport of debris and the physical clogging of the strainer. The establishment of a correlation (strainer head loss versus debris mass at 30°C) allows an extrapolation of the maximum head losses without taking into account the amount of settling debris, may be, linked to the test loop (mock-up effect). The debris carried to the strainer (roughly 40 to 45% of the debris source term) generates at 80°C (with chemistry) a very quick increase of the pressure drop across the strainer (up to 7 kPa). After 2-3 days, a pressure drop was observed on the strainer, what could be due to the chemical effects.

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[1] **S**canning **E**lectron **M**icroscopy / **E**nergy **D**ispersive X-Ray **S**pectroscopy

An extrapolation to the total mass of debris, without taking into account the valorization of the debris sedimentation, assumed to be transported to the strainer and for a low temperature (30°C) leads to the head losses threshold of 25 kPa (*extrapolated from 11-14 kPa*) being reached. This result has to be compared to the value of the maximal head loss allowing operation of the safety pumps.

The observations realized during these campaigns of tests demonstrate the need to carry out tests at high temperature with the real "chemistry" in the water to highlight potential phenomenon and to provide relevant assessments. Another test set is also foreseen in 2019, to complete our understanding and propose validated conclusions for the IRSN safety expertise.

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