Chapter 5

Research on Recirculation Cooling under Accident Conditions

If a leak occurs in a PWR reactor coolant system and is not compensated by the chemical and volume control system (CVCS), reactor core cooling is ensured by injecting borated water. This is done by the safety injection system (SIS). In order to remove residual heat and preserve the integrity of the reactor containment building, the containment spray system (CSS) may also be required. Sodium hydroxide is added to the spray water to favor retention inside the reactor building of radioactive substances such as iodine-131.

The borated water required for these operations is initially drawn from the tank of the treatment and cooling system of the water of the spent fuel storage pools (RWST[42]), which has an approximate capacity of 1600 m^3 in a 900 MWe pressurized water reactor. When the low level threshold is reached in this tank, the SIS and CSS automatically switch over to recirculation mode. In this mode, they take in water that has been collected in the sumps located at the bottom of the reactor building (Figure 5.1). This recirculation mode may be required over very long periods of time to cool the fuel assemblies. It must be highly reliable as it is fundamental in avoiding fuel assembly damage and preventing a core melt accident.

The sumps at the bottom of the reactor building are equipped with a strainer system designed to ensure that the quality of water downstream of the strainers is compatible with the operation of SIS and CSS components, and with fuel assembly cooling. Debris can be generated as a result of the break (destruction of equipment by shock wave or jet) or

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[42] Refueling Water Storage Tank.

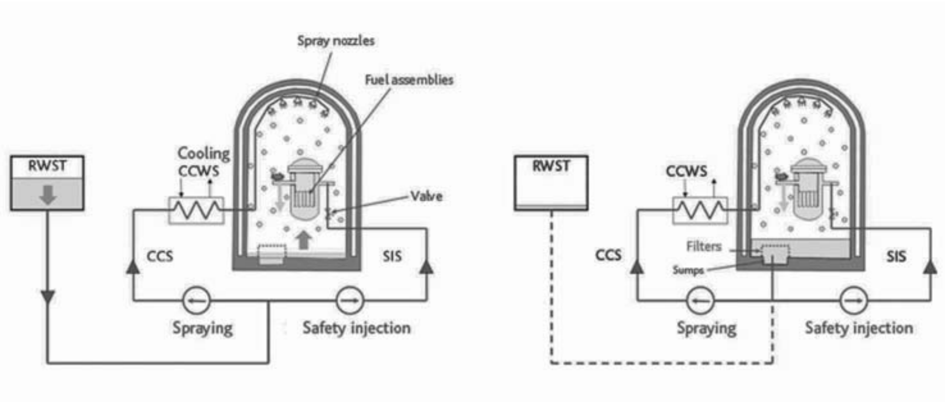

Figure 5.1 Simplified diagram of SIS and CSS operation in direct injection mode (left) and recirculation mode (right) – the component cooling water system (CCWS) is also responsible for cooling some pumps in the systems shown. © IRSN.

ambient conditions in the reactor building (temperature, irradiation, etc.), or it may already be present in the reactor building (dust, etc.). The flow of water (from the break in the reactor coolant system or CSS washdown) can then transport this debris to the sumps.

Depending on its characteristics (size and weight), some of this debris may be carried as far as the strainers and form a debris bed, which can lead to strainer clogging as a result of physical or chemical effects. The main risk involved is the impeding or obstruction of water recirculation.

Strainers must be sized (in terms of surface area and mesh size) to:

- prevent SIS and CSS pump cavitation failure. This risk is reduced by the use of sufficiently large screen surface areas;
- ensure the operation of components located downstream of the strainers, as well as fuel assembly cooling. This can be guaranteed by a suitable strainer mesh size.

5.1. Operating experience feedback and research topics

Risks relating to the loss of recirculation cooling capability in light water reactors were identified in the 1970s, and were the subject of the U.S.NRC Regulatory Guide RG 1.82 issued in 1974[43].

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[43] In 1974, the U.S.NRC published its "Regulatory Guide 1.82", which describes the methods and practices acceptable to U.S.NRC staff for addressing all the issues generally related to emergency recirculation cooling after a loss-of-coolant accident and applicable to PWR- and BWR-type light water reactors. The guide was gradually updated to reflect operating experience feedback and new knowledge resulting from research and development. This initial version of the Regulatory Guide was applied to French nuclear power plants designed by Westinghouse. The version currently in force is Revision 4 released in March 2012 [1].

During the early 1990s, however, several incidents occurred in boiling water reactors (at Sweden's Barsebäck plant, and at the Perry and Limerick plants in the United States), which raised new questions on the risk of strainer clogging. The incident that affected reactor 2 at the Barsebäck BWR plant in Sweden [2] on July 28, 1992 was caused by the inadvertent opening of a valve. The resulting steam jet produced 200 kg of fibrous debris, composed mostly of insulating material. Half of it was carried to the suppression pool or wetwell[44], leading to a significant increase in head loss across the emergency core cooling system strainers after 70 minutes. Given the modest size of the equivalent break (corresponding to the valve diameter), the quantity of debris appeared far greater than could have been expected based on RG 1.82 in its first revision in November 1985.

In view of the incidents mentioned above, international investigations focused especially on boiling water reactors. Research results concerning this type of reactor revealed that the quantity of debris generated by a pipe break in the reactor coolant system could exceed by far the quantities considered until then, based on earlier research. They also showed that the debris could be finer (and therefore more easily transportable) and that some combinations of debris (fibers with particles, for example) could augment the risk of strainer clogging. These results can be found in many documents, including the report NUREG[45] 6224 issued in 1995 [3] on the study of strainer blockage in BWR engineered safety systems.

This led to new studies being initiated in the late 1990s by industry, laboratories and research organizations, with active involvement on the part of IPSN.

Research work also revealed further issues relating to the chemical effects associated with the pH and temperature of the solution, and their impact on the risk of strainer blockage, as well as the effect of debris passing through the strainers on the functional performance of SIS and CSS engineered safety system components, and on fuel assembly cooling.

Research carried out since 1974, and incident analysis have raised many questions, for the most part in studies on the following topics.

► Characterization of debris likely to reach the strainers

It is essential to characterize the debris (type, quantity and size) likely to be transported to the strainers in order to assess: the risk of strainer clogging; the operation of components located downstream of the strainers; and fuel assembly cooling.

By far, the greatest amount of debris is directly produced by the shock wave generated by the break. In particular, it comes from the destruction of insulating material (glass fiber, Microtherm, etc.) on equipment located near the break (such as piping and steam generators), as well as paint and concrete. The quantity of debris depends especially on the pressure field induced by the break and the strength of the material

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[44] Pool located at the bottom of the reactor building from which the engineered safety systems draw water.

[45] Nuclear Regulatory Report.

of which the debris is composed. Size and shape varies (fibers a few millimeters in length, particles a few micrometers in diameter).

Other debris is generated by ambient conditions (temperature, humidity, irradiation) in the reactor building. It may be composed of chips (a few mm^2) or particles (a few µm in diameter) of worn or damaged paint.

Lastly, some debris, such as dust or grease, is found in the reactor building before the accident. Referred to as latent debris, it can be entrained in streams of water and must be taken into consideration in strainer design.

► Debris transport to strainers

Some debris can be transported (Figure 5.2) to the bottom of the reactor building in the water flowing through the break and in containment spray washdown. Other debris can be trapped in retention zones – for example on floors and gratings. This is called vertical debris transport.

During the switchover to recirculation mode, the debris transferred to the bottom of the reactor building can, depending on its size or weight, be transported to the SIS and CSS sump strainers. This is referred to as horizontal transport.

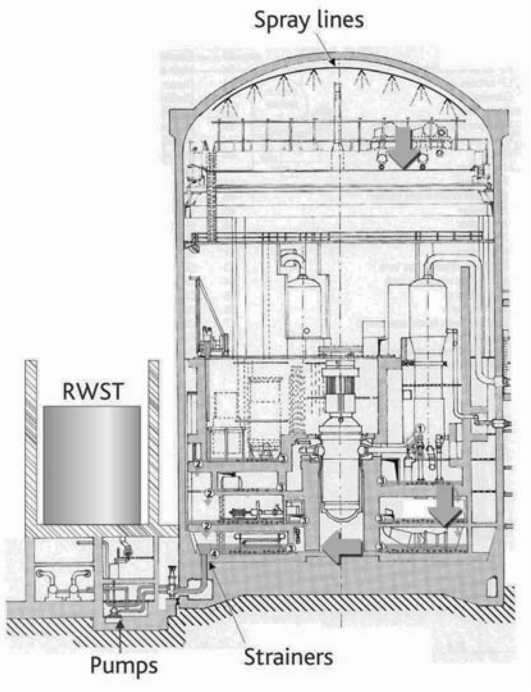

Figure 5.2 Illustration of debris transport to sump strainers (900 MWe PWR containment building). © IRSN-source EDF.

► Assessment of strainer head loss and clogging risk

The debris transported to the strainers may either agglomerate in the strainer mesh and form a debris bed over the entire screen surface area (Figure 5.3), thereby increasing the head loss across the strainer terminals, or, depending on its size or the permeability of the debris bed formed, be transported downstream of the strainer, and induce "downstream" effects. Strainer head loss is determined using correlations, such as the NUREG 6224 correlation, that are used to check that there is no risk of pump cavitation failure.

In this respect, research has demonstrated that for some strainers, just a small quantity of mixed debris (fibers and particles) can lead to significant head loss across strainer terminals in recirculation mode (Figure 5.4), and thereby increase the risk of pump cavitation. This is known as the thin film effect.

► Impact of chemical effects on strainer head loss

Research work, in particular that carried out by IRSN, has shown that physical-chemical phenomena can lead to the formation of precipitates (crystals, gels) in the debris bed. The precipitates can build up and cause an increase in strainer head loss. These phenomena depend not only on water pH and temperature, but also on the characteristics of the debris in the containment, especially in the water at the bottom.

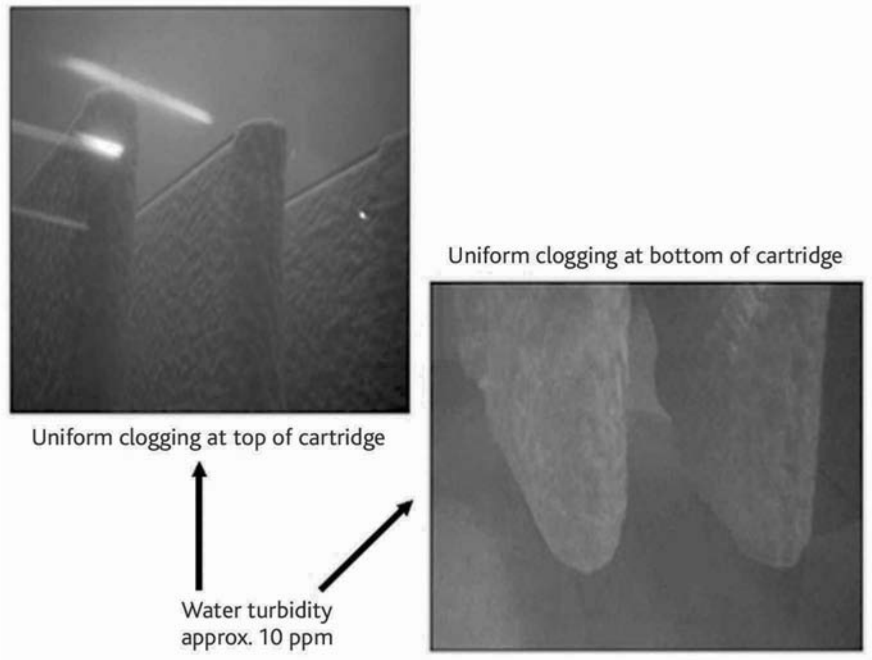

Figure 5.3 Examples of fibrous and particulate debris covering screen surfaces (qualification tests on SIS strainers for the EPR). © IRSN.

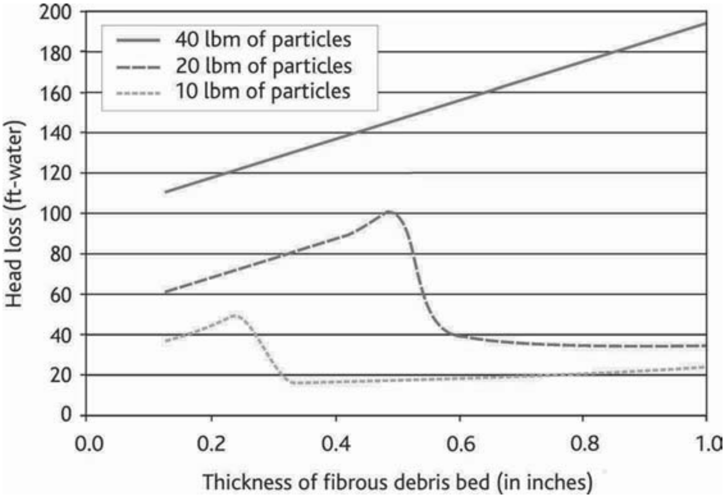

Figure 5.4 Diagram of strainer head loss peak or thin film effect [6].

► Downstream effects

Depending on strainer system characteristics (mesh, screen surface area), the debris passing through the strainers, and the chemical substances in the water, can lead to physical and chemical phenomena, such as soiling, clogging and erosion. This can impair the performance of SIS and CSS components, such as pumps, diaphragms, heat exchangers, valves and safety valves, and compromise fuel assembly cooling in the core (partial blockage of fuel assembly grids).

5.2. Past research programs and lessons learned

Following the BWR incidents that occurred in the 1990s, a considerable number of studies and research and development programs were conducted around the world. This was particularly the case in France with work carried out by EDF and IPSN (then IRSN), to obtain a fuller understanding of the phenomena involved and assess strainer system design.

As part of a knowledge-sharing initiative, OECD/NEA published a knowledge-base report [4] in 1995, following the incident at the Barsebäck plant. An updated version of the report was issued in 2013 [5]. More than ten laboratories and research organizations worked – or continue to work – on these topics for safety authorities and TSOs[46] (U.S. NRC, IRSN, etc.), designers and industry (e.g. General Electric, AREVA, EDF). Progress in some of this work is reported in a number of documents [6,7,8]. IPSN collaborated with

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[46] Technical Safety Organization.

VUEZ and the University of Trenčín (Slovakia), and with EREC (Russia) on a series of tests in experimentation loops, described in greater detail below.

EDF took part in the Nuclear Energy Institute (NEI) study and research program on recirculation issues that led to the publication of a guide [6, 7] in 2004 describing methods for evaluating strainer design for PWRs.

In an initial research program, IPSN defined and funded a number of experiments, most of which were carried out by VUEZ and EREC from 1999 to 2003. IPSN supervised the experiments. The following topics were studied:

- efflorescence of debris induced by water flow: 77 tests were performed in the ELISA facility set up by IPSN at VUEZ to study the impact of insulation type and water flow rate, temperature and quality, as well as how solid particles affect head loss due to the presence of insulation material on a strainer screen;
- vertical debris transport and crushing caused by obstacles: 30 tests were carried out in the IVANA facility, also installed at VUEZ, to assess the size of debris generated, based on the initial size of debris, spray water flow rate, and the type of insulating material considered;
- horizontal debris transport rates and debris settling in the containment: 52 tests were performed in the VITRA facility, set up by IPSN at EREC, to study the water flow rates below which debris, depending on its characteristics, settles on the horizontal floors of the containment building, and thus does not contribute to sump strainer clogging;
- strainer obstruction mechanisms: following a campaign of 15 preliminary tests, 11 full-scale tests were performed at the MANON facility, set up by IPSN at VUEZ, to assess the quantities of debris likely to seriously compromise the performance of water recirculation pumps.

In 2003, IRSN shared to the French Nuclear Installations Directorate the lessons learned from international research and, in particular, the tests mentioned above. The findings of this work raised the issue as to whether the possibility of sump strainer clogging could lead to loss of recirculation cooling in PWRs under accident conditions. In 2004, EDF decided to make a number of engineering changes to its nuclear power plants in operation, based on the NEI guide mentioned earlier [6,7] and the results of the ensuing research. These changes were implemented on reactors from 2005 to 2009. The new strainer design is now based on methods and practices developed by EDF that are specific to French reactors but also comply with the design provisions of the latest version of U.S.NRC Regulatory Guide RG 1.82.

Until the early 2000s, the mesh size of the strainers installed in French nuclear power varied with the reactor series. The strainers were vertical panels installed in the sumps in a circumferential arrangement. Based on research and development findings, two changes (decided in 2004) were implemented:

- removing Microtherm insulation, because this material can generate very small particles, making it unacceptable in terms of the risk of sump strainer clogging;

- fitting strainer systems with new strainers with a significantly larger surface area (up to 48 times that of the previous strainers).

Note that for the EPR, the strainer system adopted consists of two[47] lines of strainers installed across the path of the debris:

- basket strainers at the edge of the Internal Reactor Water Storage Tank (IRWST), which provides a reserve of borated water in the containment, at the floor openings in large components;
- strainers in the middle section of the IRWST (In-containment Refueling Water System Tank), where the spray lines leading to the pumps are installed.

Following the studies it carried out from 1999 to 2003, IRSN decided to launch a joint program with VUEZ and the University of Trenčín to study the chemical effects of the fibrous bed deposited on the strainers.

The aim was to assess how the formation of precipitates impacted strainer head loss, with engineered safety systems operating in recirculation mode, following a reactor coolant system break. The program was in two parts. The purpose of the first part was to determine the concentration of precipitates that might form. The second sought to determine the impact of precipitate formation on fibrous bed head loss, based on tests carried out in the ELISA test loop.

The program confirmed that precipitates could form in a fibrous bed and that this significantly affected strainer head loss. Tests also showed that temperature had a considerable impact on the formation, type and development of precipitates. A strainer head loss computational model was developed based on the above results. The model is also designed to provide fibrous bed porosity data.

IRSN initiated another research program to confirm the above model and consolidate knowledge concerning long-term corrosion in different types of insulating material and the precipitates that could form as a result. The program was performed using six test loops called ELISA Babies, derived from the design of the ELISA loop.

5.3. Ongoing research programs

As of 2015, many research programs were still in progress both in France (EDF and IRSN) and abroad. These are mostly concerned with studying the effects of debris on engineered safety system components located downstream of the strainers, and on fuel assembly cooling. Some research programs are also aimed at modeling physical and chemical phenomena more precisely to substantiate some strainer designs.

In 2015, for example, IRSN decided to launch new research programs involving the use of VIKTORIA, a new test loop installed at VUEZ. The aim is to evaluate the design of strainer systems used in currently operating reactors and those intended for use in the EPR, in terms of chemical effects and the effects of debris passing through the strainers.

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[47] In addition to trash racks installed on the floor of large components.

Figure 5.5 View of the VIKTORIA test loop © Brano Valach/IRSN.

VIKTORIA is an integral loop (Figure 5.5) that can simulate all the key physical and chemical phenomena for analyzing questions relating to strainer systems. It can be used for various types of pressurized water reactors for the following purposes:

- studying effects upstream of strainers including:
  - strainer head loss,
  - impact of chemical effects on this head loss,
  - gas formation,
  - the effect of back-flushing, i.e. injecting water inside the strainers to unclog them;
- studying physical and chemical effects downstream of the strainers, which entails characterizing the debris (quantity, type, size) passing through the strainers, and its impact on fuel assemblies and other components, such as heat exchangers and diaphragms.

Otherwise, research and studies carried out so far have not considered core melt situations. In the EPR, however, a core melt situation would require the use of the Containment Heat Removal System (CHRS), which is equipped with strainers. The types and quantities of debris generated in such situations could differ from those considered in design-basis transients owing to the extreme conditions (temperature, irradiation) encountered in the event of core melt. This could lead to changes in the local chemistry of the radionuclides trapped in the debris (as a result of water radiolysis) and cause precipitates. IRSN has begun an exploratory study on this topic that could lead on to more specific research over the coming years.

5.4. Simulation

The subject of debris, and its impact on recirculation cooling following a break in the reactor coolant system, involves a wide range of generally three-dimensional phenomena and disciplines, such as hydraulics and chemistry. There is a gradual increase [8] in the use of CFD simulation tools for studying issues such as debris transport, the deposition of debris on strainers, variation in head loss through a debris bed, and the risk of air and incondensable gas entrainment.

IRSN has used this type of tool for studying the representativeness of EDF tests carried out to substantiate the design of new strainers. These include tests on chemical effects. Based on the initial results of these tests, EDF considered that chemical effects had no impact on strainer head loss, owing to significant settling observed at the bottom of the test loop, and the fact that a stable debris bed could not be formed on the strainer. IRSN simulations, for example, revealed that debris was drawn down upstream of the loop strainer (Figures 5.6 and 5.7). The representativeness of these tests for the case of a reactor therefore remained to be demonstrated.

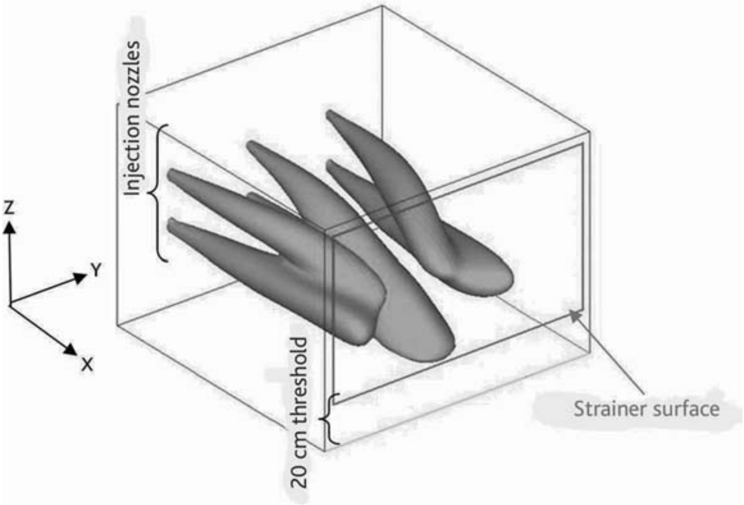

Figure 5.6 View of jets in the EDF/CEMETE model (velocities greater than 6.5 cm/s) where x is the direction of flow. © IRSN.

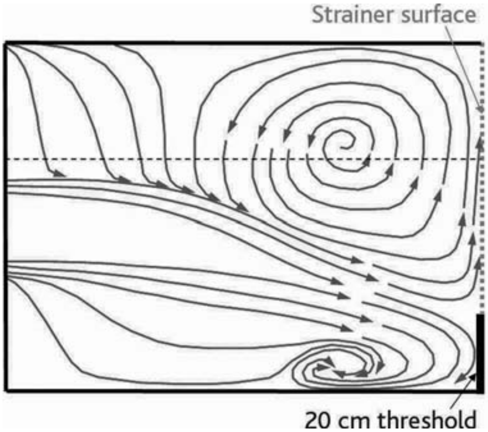

Figure 5.7 View of streamlines in the direction of flow at the middle of the EDF/CEMETE model (in the vertical plan) – the injection nozzles are on the left. © IRSN.

References

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