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Design and development of a steam generator emergency feedwater passive system for existing and future PWRs using advanced Steam Injectors (DEEPSSI)

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FINAL REPORT OF THE DEEPSSI PROJECT

(short version)

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Summary

The DEEPSSI project is a research program dealing with steam injectors. Among thermal-hydraulic passive systems, the steam injectors (also called "condensing ejectors" or "steam jet pumps") are very interesting apparatus with very specific thermal-hydraulic quantities (high velocity, very low pressure). The envisaged reactor application is the Steam Generator Emergency FeedWater System (EFWS) of Pressurized Water Reactors (PWRs). The heart of this project is the development and the testing of an innovative steam injector design. Three experimental facilities are involved : CLAUDIA in France, IETI in Italy and IMP-PAN in Poland. In these facilities, different design options have been tested and some significant improvements of the initial design have been obtained.

In addition to the experimental studies, the development of a steam injector computational model has been undertaken in order to model industrial systems based on steam injectors. The one-dimensional module of the system code CATHARE2 has been chosen to be the basis of this model. The first results obtained have confirmed the capabilities of CATHARE2 to describe the steam injector thermal-hydraulics.

1. Introduction and objectives

In a Steam Injector (SI), steam is used as an energy source to pump low pressure and temperature water. The principle is to expand pressurized steam through a converging-diverging steam nozzle (figures 1 and 2) and reach low static pressure values sufficient to suck cold water. Steam is condensed in a mixing chamber and transmits its momentum to water. Pressurized water is obtained in a diffuser, downstream an abrupt pressure increase called here: "condensing shock wave" (the nature of this "shock wave" is often a matter of deep discussions, this debate is not tackled in this paper). Usually, for nuclear reactor applications, the maximum exit water pressure (the back-pressure) must be higher than the inlet steam pressure. This is the main challenge regarding the high pressures encountered in Light Water Reactors (up to 155 bar) compared to pressures encountered in 19^{th} century steam engines.

A steam injector is considered as a passive component and its application to Light Water reactors (LWRs) was studied several times [Cattadori G. et al, 1993] [Deberne N et al, 1999] [Soplenkov K.I. et al. 1995] but, after all, no reactor implementation achieved. The reactor application envisaged here is the Steam Generator Emergency FeedWater System (SG - EFWS) of Pressurized Water Reactors (PWRs). This application consists in taking steam from the steam generator in order to pump cold water from a reservoir to feed the same steam generator.

The main objectives of the DEEPSSI project have been [Dumaz P. et al, 2003]:

- to issue functional specifications for the reactor application identified,
- to design and test an innovative high pressure steam injector (able to produce high back-pressures), in the frame of single-stage steam injectors (no combination of injectors, only one abrupt pressure increase) with annular water injection, central steam injection and no overflow in the mixing chamber,
- to develop and qualify a one-dimensional model of steam injector thermal-hydraulics, then to implement such model within the CATHARE computer code,
- to perform reactor transients calculations and analyses in order to evaluate the interest (safety, cost reduction) of a Steam Generator Emergency FeedWater System based on an innovative steam injector.

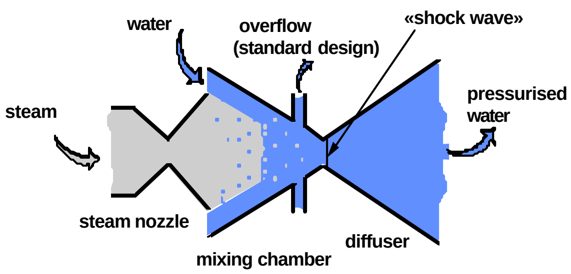


Figure 1, Schematic of a Steam Injector

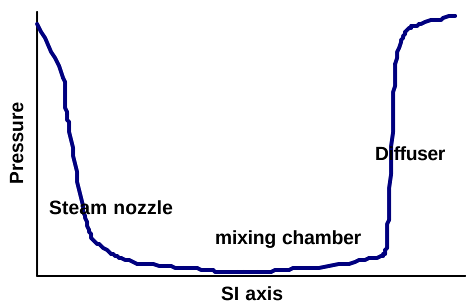


Figure 2, Typical SI axial pressure profile

2. Work Package I – Functional specifications

Given the application foreseen, the two following PWR plants have been considered in this project:

- The Russian WWER-440/213 as an existing plant for a possible retrofit with an additional Steam Injector system.
- The European Pressurized Water Reactor EPR as a new plant with a possible replacement of the presently foreseen conventional Emergency Feedwater System by a Steam Injector system.

One sets up functional specifications for each plant regarding the operation of a Steam Injector system.

<u>Possible operating modes of a SI system</u>

For a safety relevant SG feedwater system, two operating modes after an initiating event can be generally distinguished :

- Steady state operation, i.e. hot standby with SG feed flowrate against high backpressure. The feedrate is at its maximum at first to refill the SG and drops after reaching the control level because the refilling is stopped. After that the feedrate decreases continuously because of the decreasing decay heat over time (figure 3).
- Changing state operation, i.e. cool-down with SG feed flowrate against decreasing backpressure. At first the feedrate is equal to the decay heat removal. After the cool-down is started, the feedrate increases due to the additional removal of the heat stored in the component and water masses. From this level it decreases according to the course of the decay heat (figure 4).

The feedrate increase depends on the cooldown gradient, the stored heat and the time at which the cooldown is initiated. The investigation of both operating modes results in the determination of:

- a flowrate which permits the refilling of one or more partially depleted steam generators,
- a flowrate which has to be adapted to the heat to be removed to avoid overfeeding of one or more steam generators.

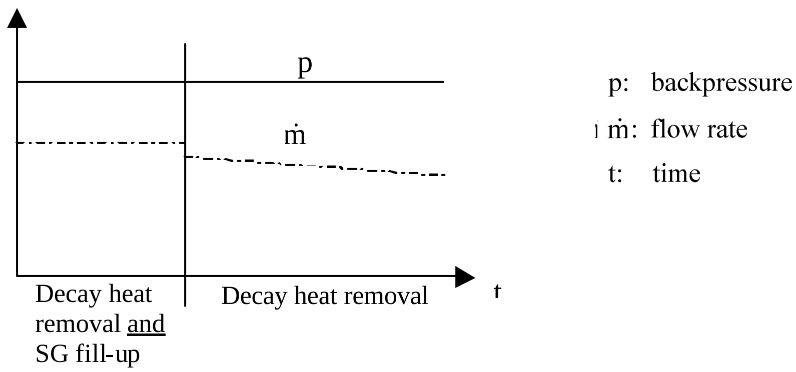


Figure 3: Steady-state mode

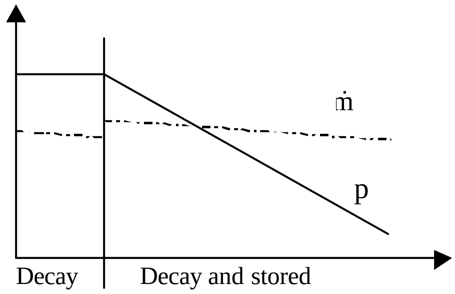


Figure 4, Changing-state mode

Steam injector system description

The two possible EFWS systems based on steam injectors are schematized in the figures 5 and 6. For the EPR case, the four SI replace the four motor-driven pumps. For the WWER case, it is an additional mean to inject water in the SGs. This leads to quite different design criteria.

In EPR where one has to replace a safety classified EFWS, one has to consider:

- a deterministic design (single failure, preventive maintenance, …),
- conservative boundary conditions,
- a strict separation of the trains,
- a mitigation of all design events.

In the WWER case, one would be in “beyond design” management (then, no deterministic design, best estimate boundary conditions, …).

Based on the previous operating modes, one has estimated the specifications required for (see the tables 1 and 2):

- the minimum and maximum flowrates (cold water sucked by the SI) and,
- the SI pressure increases (the outlet pressure minus the inlet steam pressure),

From the likely SI implementation, one has determined the available water pressure at the SI water inlet Of course, this latter will depend on the water level in the water reservoir.

These specifications are very demanding. For the most demanding case, we have to cope with a sucked flowrate of 50 kg/s for an inlet steam pressure of 97.5 bar and an outlet pressure of 115.5 bar (for the DN 125 discharge line). Taking into account the capabilities of our industrial-scale facilities, one has decided to consider solutions (like introducing a steam header) allowing to limit the specifications to 25 kg/s of water. This was already quite challenging.

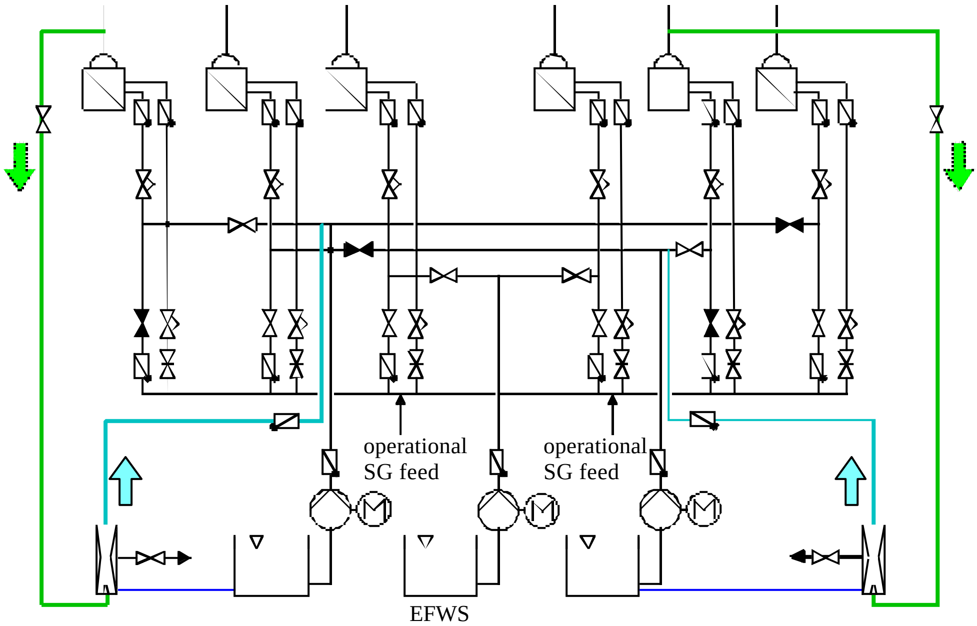


Figure 5: WWER 440-213, Possible configuration for an additional SI system

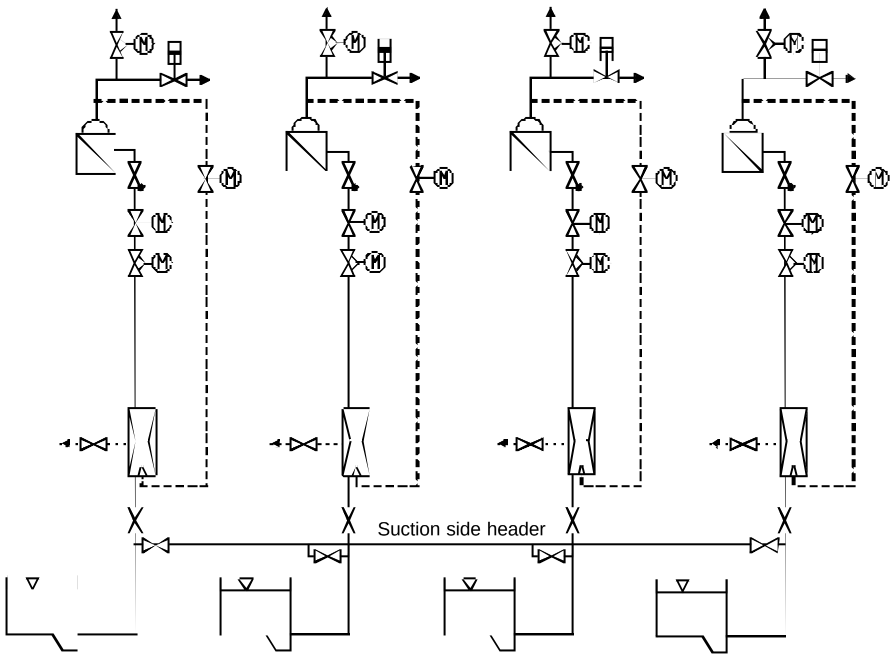


Figure 6: EPR, Possible configuration for a SI system

Table 1: WWER specification for an individual Steam Injector

Sucked water flowrate	Minimum flowrate (2 x 100% system): Not more than 2.8 kg/s at 30 °C against a SG pressure of 56.6 bar Maximum flowrate (2 x 100% system): Not less than between 4.6 and 16.7 kg/s at 30°C against a SG pressure of 56.6 bar
Pressure increase	either 3.2 bar for 4.6 kg/s at 30°C with DN 80 discharge line (0.6 bar discharge line; 1 bar steam line; 1.6 bar geodetical height) or 9.7 bar for 16.7 kg/s at 30°C with DN 80 discharge line (7.1 bar discharge line; 1 bar steam line; 1.6 bar geodetical height) Pressure losses for necessary control valves have to be added.
Water inlet pressure	some 1.8 bar at Steam Injector start-up some 0.35 bar at pool nearly empty Pressure losses for necessary control valves have to be considered.

Table 2; EPR specification for an individual Steam Injector

Sucked water flowrate	Minimum flowrate: Not more than 2.5 kg/s at 50 °C against a SG pressure of 96 bar Maximum flowrate: Not less than 50 kg/s at 50 °C against a SG pressure of 97.5 bar 25 kg/s at 50 °C against a SG pressure of 97.5 bar, considering additional measures like opening the suction header during preventive maintenance (PM), introducing a steam header, or doubling of valves or two Steam Injectors per train
Pressure increase	For 25 kg/s at 50 °C either 12 bar with DN 100 discharge line (8 bar discharge line; 1 bar steam line; 3 bar geodetical height) or 7.5 bar with DN 125 discharge line (3.5 bar discharge line; 1 bar steam line; 3 bar geodetical height) Pressure losses for necessary control valves have to be added. For a higher feedrate the pressure drop has to be re-assessed.
Water inlet pressure	1.1 bar at Steam Injector start-up 0.37 bar at pool nearly empty Pressure losses for necessary control valves have to be considered.

3. Work Package II - Experimental studies

Three facilities were involved in these studies : a laboratory-scale facility (IMP-PAN), an industrial-scale facility limited to 30 bar (CLAUDIA) and another industrial-scale facility limited to 80 bar (IETI). Industrial-scale facility means that the experimental flowrates and pressures are close to those of a SI based EFWS system. Four experimental campaigns have been conducted (one in IMP-PAN, two in CLAUDIA and one in IETI).

The first objective of the experimental studies was to find a steam injector design which can fulfill the previous specifications. Innovative SI designs have then been identified and tested. The second objective of the experimental studies was to provide a data base for the SI physical phenomena modeling.

3.1 Test section design and test specifications

The base SI apparatus considered is a very simple double converging-diverging sections (figure 7). It has been decided to have an annular injection of water in the mixing chamber and to avoid the use of overflow ports inside the mixing chamber.

The two considered design innovations are: an “axial overflow” and an “axial needle”. Both devices are inserted within the diffuser and can be moved axially (figure 7). The idea to use an axial overflow came from the observation of an annular two-phase-flow structure up to the end of the mixing chamber. The overflow tube, inserted in the SI diffuser, should remove mainly the centerline steam which is not condensed at the end of the mixing chamber, steam not very useful in term of pressure recovery because its momentum is much lower than the liquid momentum. In addition, the condensation shock wave being located between the diffuser wall and the overflow tube, the shock wave flow area is reduced in comparison to the configuration without the overflow insertion. This should lead to an increase of the maximum backpressure given this latter is expected to be inversely proportional to the shock wave flow area (ideal case with a plane shock wave). In general, it is known that an easy SI start-up requires a large mixing chamber throat area, on the other hand, high performances require a small throat area. In order to explore the minimum throat size for the start-up and for the steady state, an axial needle was proposed.

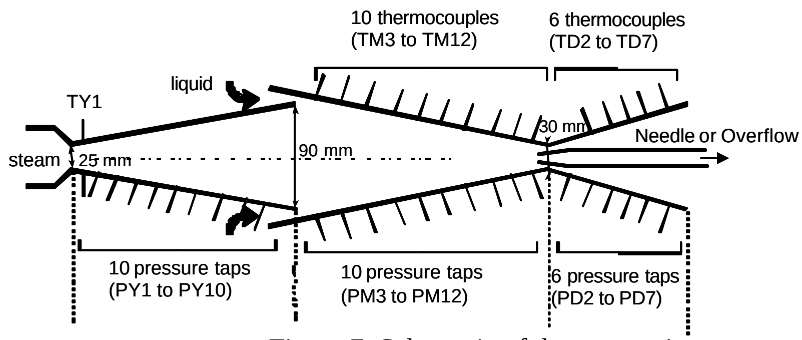


Figure 7: Schematic of the test section

From the previous functional specifications and taking into account the CLAUDIA and IETI limitations, it has been decided to consider the following range of parameters as the “industrial objectives»:

- inlet steam pressure (saturated) : from 10 to 80 bar,
- inlet water flowrate (at room temperature) : from 4 to 25 kg/s.

The reference inlet water temperature considered is about 20°C (room temperature). Some IETI tests have been performed with a higher temperature: about 40°C.

For the lab-scale tests, the main concern was the scaling of the test section given the low available maximum steam flowrate and pressure : 0.042 kg/s at 5 bar. Based on a limited scaling analysis, it has been decided to consider dimension reductions by about a factor 3 compared to the CLAUDIA and IETI test sections.

As far as the instrumentation is concerned, the different test sections used were equipped with conventional pressure and temperature measurements. The thermocouples were installed in wall holes, the head being just on the inner surface. Therefore, such thermocouples measure the temperature of the flow close to the wall. In addition to this conventional instrumentation, different techniques have been developed to measure void fractions.

For all the DEEPSSI tests, the test procedure is almost the same:

- the test section being at room pressure and temperature, the exit valve being fully opened, the water injection is opened and a constant water flow is imposed.
- then, the steam injection is actuated. In contact with the mixing chamber water, steam starts to condense and the mixing chamber pressure decreases. For a constant inlet

steam pressure, a constant steam flowrate is obtained (critical flow in the steam nozzle throat). When the flow is supersonic up to the end of the diverging section of the steam nozzle, it is said that the steam injector is "started".

- The exit valve is progressively switched off in order to increase the SI exit pressure, a condensation shock wave appears in the diffuser. For a high enough exit pressure, the shock wave is attached to the mixing chamber throat, If we keep increasing the exit pressure, suddenly, the shock wave enters inside the mixing chamber. A very unstable regime follows, the exit pressure decreases rapidly, and this is called the SI stalling.
- The testing is quickly ended by closing the steam injection.

3.2 Laboratory-scale tests

These experiments mainly deal with the second objective of the DEEPSSI experiments, they should provide a modeling support. Using a transparent test section (figures 8 and 9), the aim of the tests is to improve the understanding of the SI basic thermal-hydraulic phenomena.

The results of these experimental investigations showed pressure and temperature profiles along the injector typical of this kind of devices (figures 10 and 11). That is, during steady-state operation (after the SI start-up), low pressures and low temperatures inside the mixing chamber and an abrupt pressure increase at the beginning of the diffuser (the "condensation shock wave"). These mixing chamber pressures and temperatures were independent of the value of the diffuser outlet pressure (the back-pressure). This is usually the indication of the supersonic nature of the mixing chamber two-phase-flow.

The void fraction measurements showed a quite constant void fraction within the mixing chamber and confirmed the complete condensation downstream the condensation shock wave. The visualization method (stroboscope lamp with CCD camera) combined with the other measurement results suggest the two-phase-flow structure depicted on the figure 12. It can be seen that for both low and high backpressures, the flow in the mixing chamber is annular almost up to the throat.

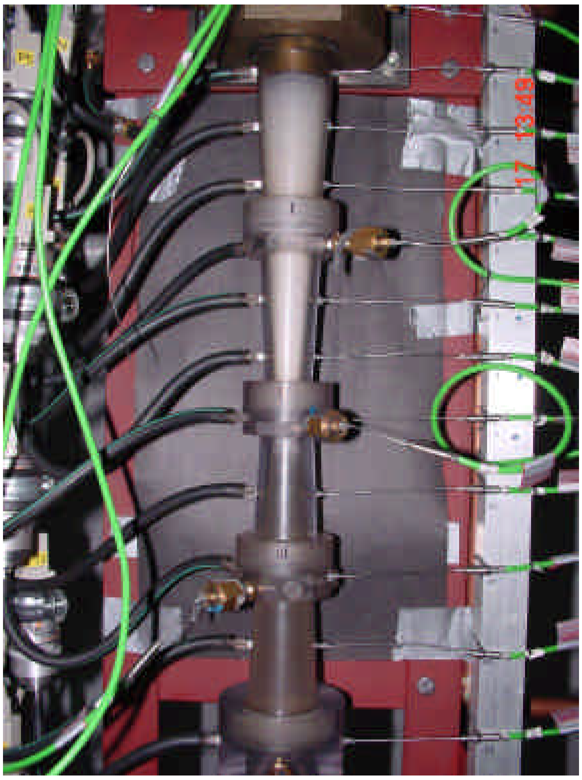


Figure 8. IMP-PAN lab-scale facility, mixing chamber and diffuser

Figure 9. IMP-PAN lab-scale facility, the diffuser

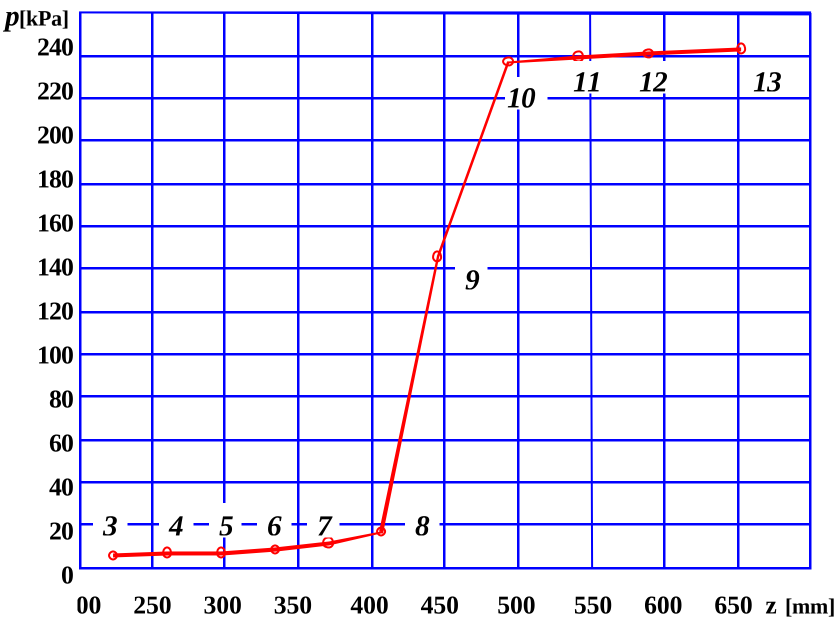


Figure 10. Pressure profile for, qlo = 0.51 kg/s, Pvo = 3.44 bar (z is the distance from the steam nozzle entrance, the measurement numbered 9 is the first point within the diffuser)

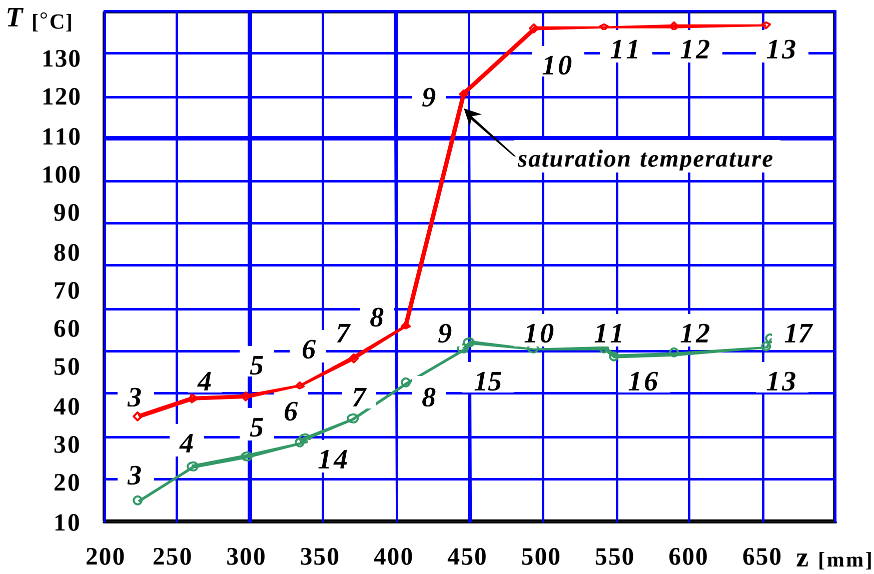
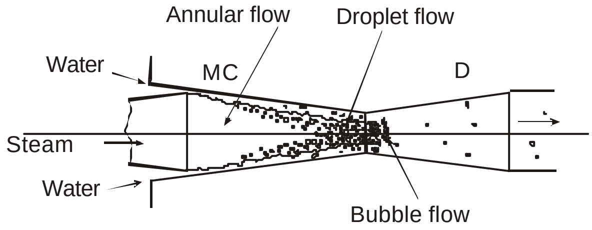
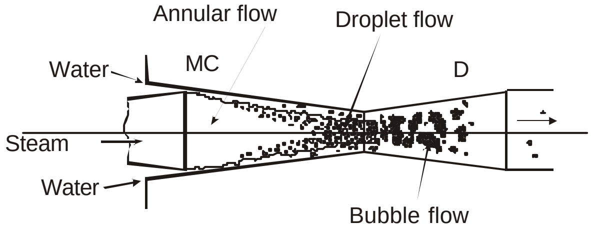


Figure 11, Temperature profile for, qlo = 0.51 kg/s, Pvo = 3.44 bar.



a) High back pressure.



b) Low back pressure.

Figure 12. Sketch of the flow patterns at different backpressures.

3.3 first series of CLAUDIA tests

The first series of CLAUDIA tests performed was devoted to the validation of design innovations at medium steam pressures (up to 30 bar) and with realistic water flowrates. The base test section used (figure 7) is very similar to the DIVA test section [Dumaz et al, 1997]. The main difference is the possibility to insert within the diffuser an the axial overflow or an axial needle (figure 7). Both devices can be moved axially, from a downstream position (with no modifications of the mixing chamber throat) up to an upstream position, the device head being slightly inside the mixing chamber (with a reduction of the mixing chamber throat area).

These tests are called "component tests" because the backpressure variation is controlled by an exit control valve and the inlet water flow is controlled. In a real industrial system, these boundary conditions would vary as a function of the overall system design. In these tests, for three steam pressures (10, 20 and 30 bar) and various water flowrates, the SI performances are investigated by increasing the backpressure up to the SI stalling (end of a stable regime, see the explanation just above). A conventional instrumentation was used here (flowrate, pressure, temperature), The schematic of the test section implementation is given on the figure 13.

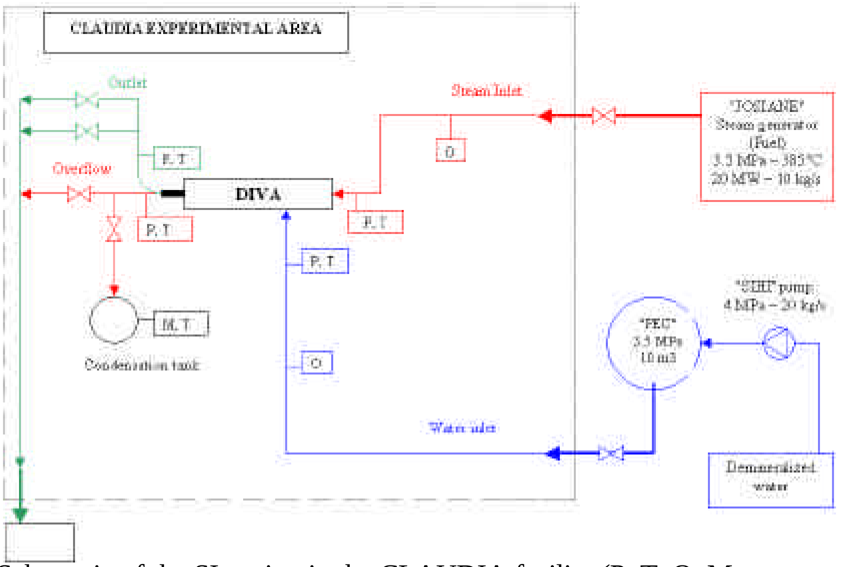


Figure 13. Schematic of the SI testing in the CLAUDIA facility (P, T, Q, M, mean pressure, temperature, flowrate and mass measurements).

<u>Test results, axial overflows</u>

Two different overflows were tested: a small one (16 mm inner diameter) and a large one (20 mm inner diameter).The start-up procedure consists in opening first the water flow and then the steam flow, the SI outlet being at atmospheric pressure and the axial overflow being in the downstream position. For these conditions, an easy start-up was always obtained. The mixing chamber throat diameter (30 mm) was chosen to obtain this easy start-up.

Start-up with the axial overflow being inserted up to the mixing chamber throat was tested. This was much more difficult. For low water flowrate (about 6 kg/s) and enough steam pressure (20. bar), the start-up was obtained. Unfortunately, the exploration of the start-up conditions, with different axial overflow positions, was very limited.

As far as SI performances are concerned, a significant increase of the maximum exit pressure (up to 30 %, figure 14) was obtained in comparison to the results without the axial overflow. For the small size overflow, this maximum exit pressure was obtained by inserting the overflow slightly inside the mixing chamber (about 30 to 50 mm depending on the steam pressure and the water flowrate). The measurement of the mass flowrate through the overflow in function of its insertion confirms that the core flow close to the exit of the mixing chamber is mainly steam. Using the larger diameter overflow, no success to reach higher backpressures was obtained. Moreover these tests evidenced a much higher flow through the axial overflow. This means that a significant part of the flow is liquid and that this overflow is too large regarding the initial objective to release mainly steam through the overflow duct.

<u>Test results, axial needle</u>

Only one needle was tested. Its largest diameter is 25 mm and this means that for a full insertion of the needle within the mixing chamber (+100 mm related to the mixing chamber throat), the throat area is reduced by a factor 3.3. As far as the start-up is concerned, for the usual water flowrates tested during this phase (6 to 7 kg/s), the maximum needle insertion inside the mixing chamber can be at about +35 to +40 mm, leading to a throat area reduction of 15% to 20%. This shows the rightness of the nominal throat area (30 mm of diameter) regarding the start-up problem.

For a started apparatus, the needle can be further inserted up to a position leading to the SI stalling. This maximum upstream position increases with the decreasing of the water flowrate. For 7 kg/s of water, the needle can be fully inserted (+100 mm). For this position, the maximum exit pressure can be slightly above the steam pressure (figure 15). For a started SI, a limited exploration of the minimum water injection has been undertaken. This minimum water flowrate was between 4 to 5 kg/s. This is higher than the minimum flowrate given in the functional specifications: 2.5 kg/s. Quite clearly, the range 2.5 to 25 kg/s, is very demanding for a SI.

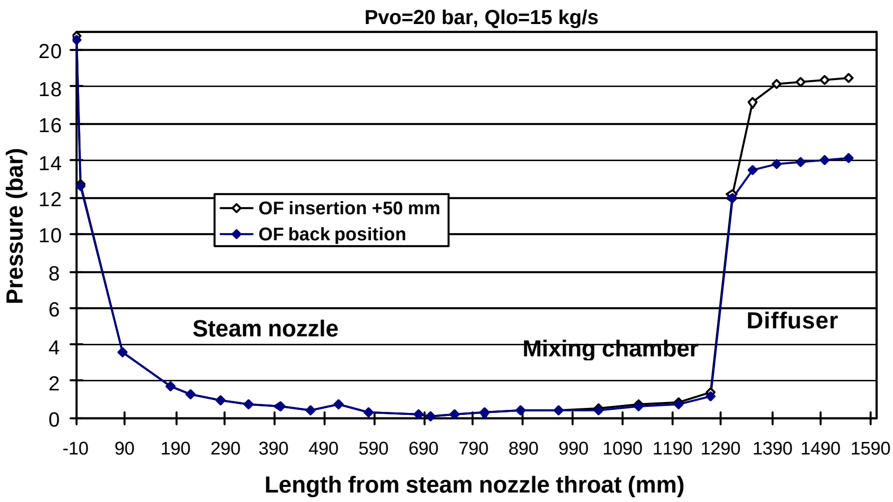


Figure 14, Pressure profiles measured: with the axial overflow (OF) in its back position and with the axial overflow inserted (16 mm diameter overflow)

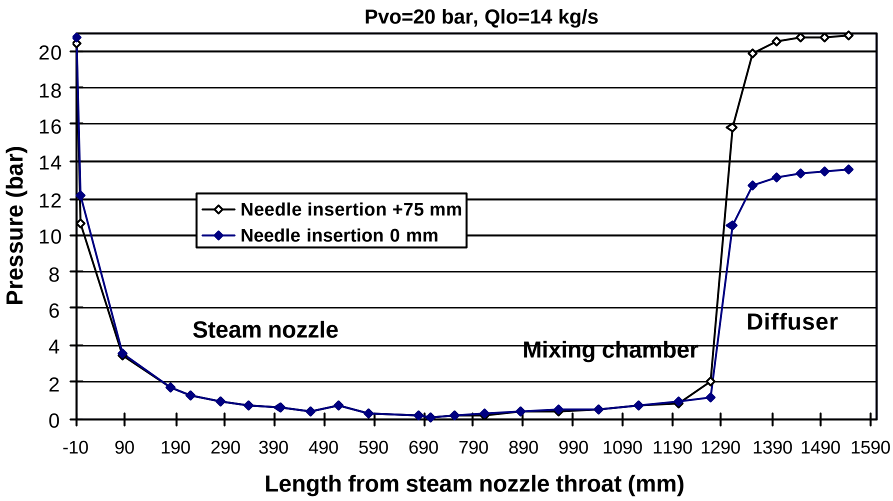


Figure 15, Pressure profiles measured: with the needle in a back position and with the needle inserted up to its maximum upstream position.

3.4 IETI tests

For the IETI tests, a slightly different test section (compared to the CLAUDIA test section) has been used but the differences are quite minor (1 mm reduction of the mixing chamber throat diameter). In order to increase the maximum backpressure, and taking into account previous CLAUDIA results, some modifications of the axial overflows and the axial needle were proposed.

The Steam Injector start-up and performance under different geometrical configurations and with different steam pressures and water flowrates have been investigated. As for the CLAUDIA tests, "component tests" have been carried out in the IETI facility, but with a steam pressure up to 80 bar.

A large size overflow (15.7 mm inner diameter), a small size overflow (12.7 mm inner diameter) and a needle have been tested. Three steam pressures (30, 55 and 80 bar) were considered for a water flowrate up to 25 kg/s.

The start-up tests with the overflow and the needle showed that the start-up is very difficult when these devices were not in their downstream position. It is worth noting that in IETI, the available inlet water pressure is low (few bar, in CLAUDIA, one can use 30 bar). Therefore, the water flowrate cannot be well controlled during a start-up procedure due to the mixing chamber pressure fluctuations. This is the likely reason explaining this difference between the CLAUDIA and the IETI tests.

For a started SI, the maximum insertion positions of the three devices were determined obtaining: +45 mm for the large size overflow, +75 mm for the needle and +35 mm for the small size overflow. The SI performances were determined with the insertion positions derived from previous tests. The highest SI backpressure was obtained with the needle inserted at +75 mm: the exit pressure reached 92% of the inlet steam pressure. With the needle extracted, only 71% of the inlet pressure was obtained (figure 16). With the needle at +100 mm, instabilities in the flow regime were observed that affected the SI performance. As far as the overflows are concerned, the early break of the flexible overflow discharge line has limited the test campaign.

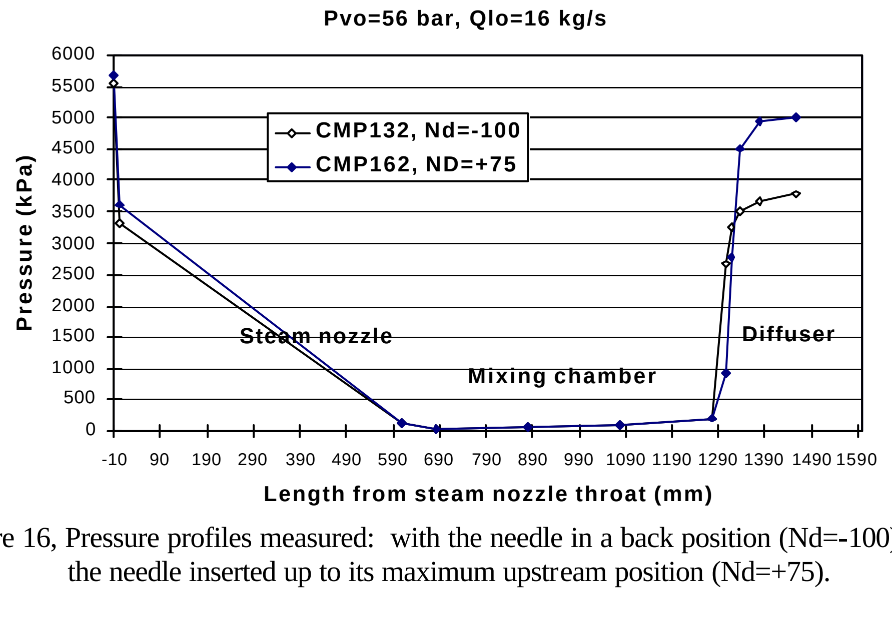


Figure 16, Pressure profiles measured: with the needle in a back position (Nd=-100) and with the needle inserted up to its maximum upstream position (Nd=+75).

3.5 Second series of CLAUDIA tests

That was the last DEEPSSI experimental campaign. Some modifications of the axial overflow and the axial needle have been proposed and tested taking into account previous results (Both IMP-PAN, IETI and CLAUDIA results). The objective was again to attempt improving the SI apparatus performances. These modifications have been driven by the idea to have a more constant flow area just downstream the mixing chamber throat.

The results obtained were disappointing because we do not increase the maximum exit pressure compared to the first series of CLAUDIA tests. The maximum exit pressure over the inlet steam pressure ratio was about 1.03 and like in the first series, it has been obtained for medium steam pressure and water flowrate (20 bar, 13 kg/s).

For this second series of tests, one developed a mixing chamber local void fraction measurement using optical fibers. Each optical probe has a Sapphire head to cope with the temperature, pressure and high veloc ity levels that might be encountered in the mixing chamber. The fibers were mounted on a tube which can be moved and inserted in the mixing chamber perpendicularly to the SI axis. It was foreseen to measure the radial void fraction profile on two axial positions.

One had significant difficulties to operate these optical probes. In fact, they did not resist to the mixing chamber flow conditions. After preliminary testing, it was decided to use the second axial position only (just upstream the mixing chamber throat). In this position, one was expecting less severe condition, but, after all, the three available optical probes were damaged.

Thus, very few void fraction profiles have been measured (figure 17 for example). Taking into account all the problems encountered, one has a limited confidence in the results obtained. At least, the profiles measured confirm the annular flow pattern within the mixing chamber.

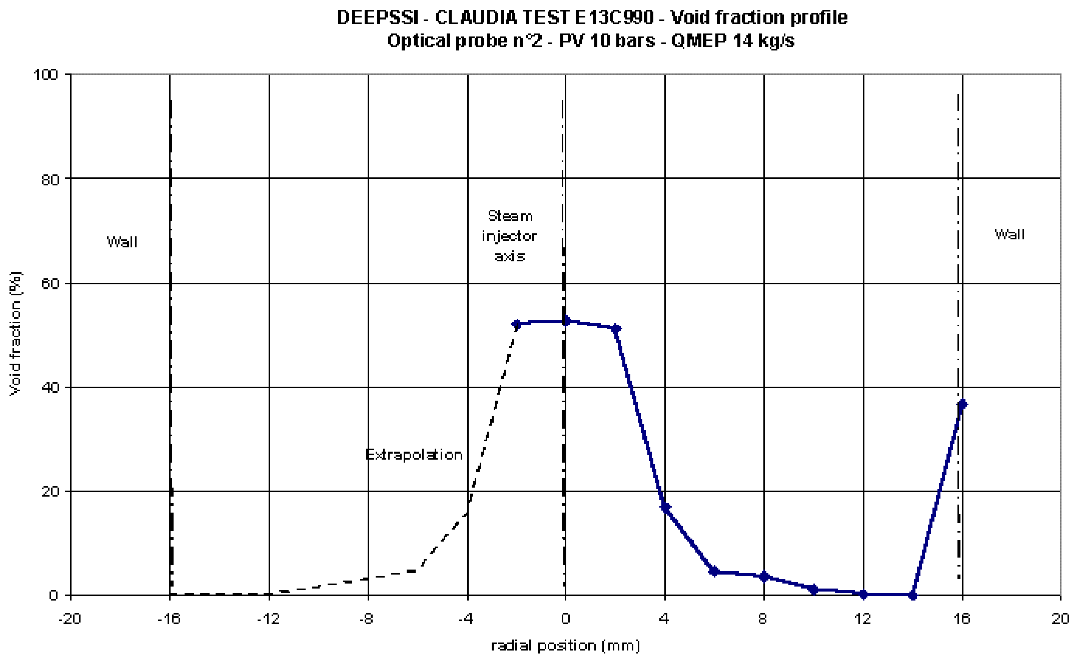


Figure 17, Radial void fraction profile measured by the optical probe

4. Work Package III – Modeling development

CATHARE2 is a best estimate thermal-hydraulic code devoted to LWR accident analyses. It is developed by CEA and it is funded by Framatome-ANP, EdF and IRSN. The development of a specific 1D CATHARE2 module for steam injectors was one of the main objectives of this project. This 1D module had to model the steam nozzle, the mixing chamber and the diffuser of the steam injector.

In fact, the availability of a computational model able to reproduce the functioning of such apparatus was considered of great importance for two reasons:

the capability in determining the SI stability region and maximum backpressure may serve to support the SI design for instance to optimize the geometry.

the possibility to simulate the whole plant with CATHARE (using other CATHARE modules) allowing the evaluation of SI reactor applications.

The analytical studies on the CATHARE code have concerned on one hand, the development of specific correlations describing the nominal SI functioning, and, on the other hand, the optimum nodalization able to overcome some numerical problems and some limitations in the SI geometrical description.. The CATHARE2 version used in the frame of this project (by all the users) is the V1.5A mod.8.1.

4.1 Development of the SI CATHARE module

The CATHARE 1D thermal-hydraulic model is based on the two-fluids six-equations model. The mass, energy and momentum balance equations are solved to calculate the fluid pressure, the void fraction, the steam and water velocities and the steam and water temperatures. The standard CATHARE correlations for heat, mass and momentum transfers were developed for LWR applications. The SI thermal-hydraulic values being very different from those encountered in these LWR applications, the standard CATHARE code cannot reproduce the SI pressure and temperature axial profiles, especially within the mixing chamber. In fact, due to the difference of velocities at the mixing chamber inlet, the CATHARE two-phase flow map gives a pure mist flow which is obviously wrong.

So new heat and momentum transfer correlations have been developed for the SI mixing chamber assuming an annular flow inside the mixing chamber (for a started SI). For the steam nozzle and the diffuser, it appeared that the standard correlations were acceptable. These new correlations are:

the liquid to interface heat flux: $q_{le} = 2{,}5\ 10^6\ a_i\ \rho_V\ (T_{sat}(P) - T_L)$

and the interfacial friction:?$\tau_i = 0{,}05\ a_i\ \rho_V\ (V_V - V_L)^2$

with $a_i = \frac{4\sqrt{\alpha}}{D_h}$ (the interfacial area density for an annular flow).

Both correlations are purely empirical correlations. The constant factors $2{,}5\ 10^6$ and 0,05 were determined by fitting the CLAUDIA temperature and pressure profiles. These correlations are actuated for a started SI, the standard correlations being used during the SI start-up when the mixing chamber fluid velocities are small. The relevance of these correlations will be demonstrated using IMP-PAN and IETI results.

Another significant point is the prediction of the maximum back-pressure (which means the prediction of the SI stalling). CATHARE tends to overestimate this maximum backpressure. To improve this prediction, it has been proposed to:

- add a singular pressure drop coefficient to take into account the geometrical shape of the steam nozzle (sharp edges at the entrance), in addition, this improves the CATHARE prediction of the steam nozzle mass flowrate,
- add a regular pressure losses in the second part of the mixing chamber.

This latter may be justified as followed. CATHARE, calculates a plane condensation shock wave. In reality, this shock wave is not plane and has a certain thickness. This leads to more momentum losses and this is taken into account by adding these regular pressure losses.

4.2 Validation of the SI CATHARE model

The DEEPSSI experimental program has produced a large amount of data for the validation of the SI CATHARE module. A wide range of operative conditions and configurations characterize the program: steam pressure (3 to 78 bar), liquid mass flowrate (0.55 to 25 kg/s), injector geometry and especially the mixing chamber geometry (with or without needle or axial overflow). Three CATHARE input decks have been developed for the three test sections.

A validation matrix has been defined considering all tests performed on the three different facilities. The tests have been selected in order to be representative of the different conditions investigated. The tests with overflow were not included in this matrix because, on one hand, the overflow configurations did not give the highest performances (compared to the axial needle), and, on the other hand, the development of a specific SI axial overflow modeling should have been undertaken.

More than 30 tests taken from the four experimental campaigns have been selected. Two configurations, with the needle inserted and without any device inserted, have been considered for the industrial test section (CLAUDIA and IETI). IMPAN tests extend the validation matrix to low pressure and flowrate.

The instrumentation provides the axial profiles of pressure and temperature along the apparatus. These profiles are the main experimental result compared with the CATHARE calculations. As mentioned above, it has been necessary to add some pressure losses. The whole test matrix has been recalculated with these additional losses. In general, this steam injector model gives the maximum backpressure of the apparatus within 10% of accuracy.

The figures 18 and 23 show these comparisons when the maximum backpressure is reached just before the SI stalling. As expected, because the new set of correlations have been tuned on the CLAUDIA tests, the calculations reproduce quite well the profiles measured in this test section (figures 18 and 19). In spite of the quite different conditions that characterize IETI and IMP-PAN tests, the calculated profiles are still in good agreement with the experimental ones (figures 20 to 23). Though these new correlations are very simple, they allow simulating with sufficient accuracy the behavior of the apparatus in steady state conditions.

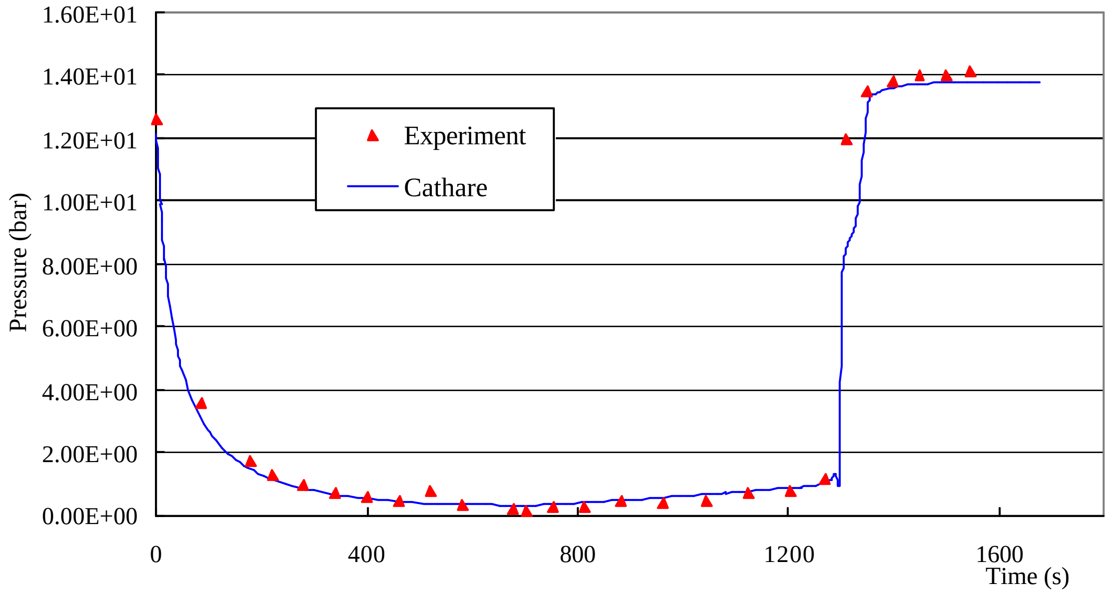


Figure 18, CLAUDIA test E40C20 (without needle) - Pressure profile

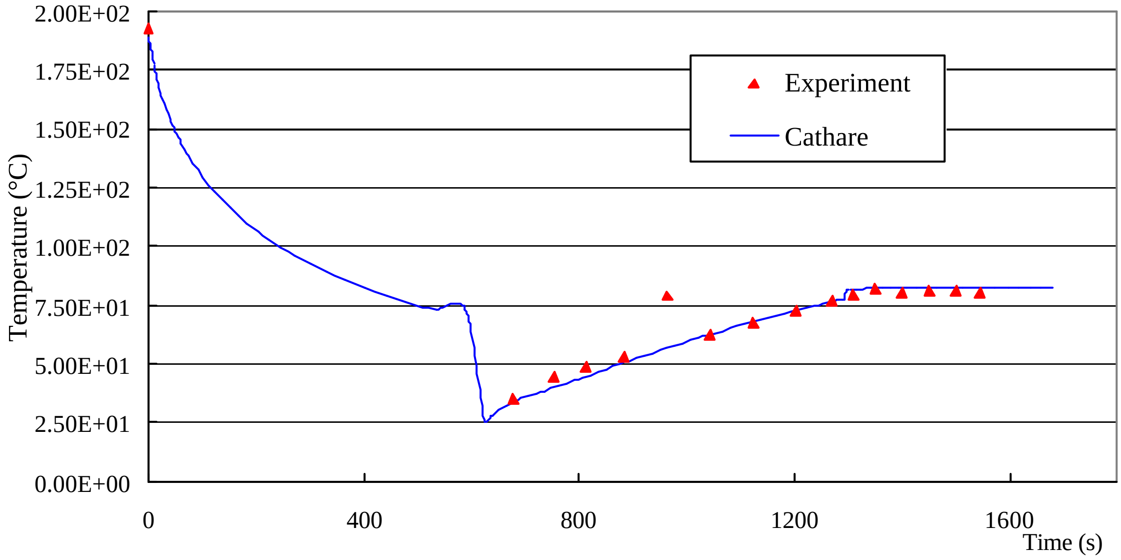


Figure 19, CLAUDIA test E40C20 (without needle) - Temperature profile

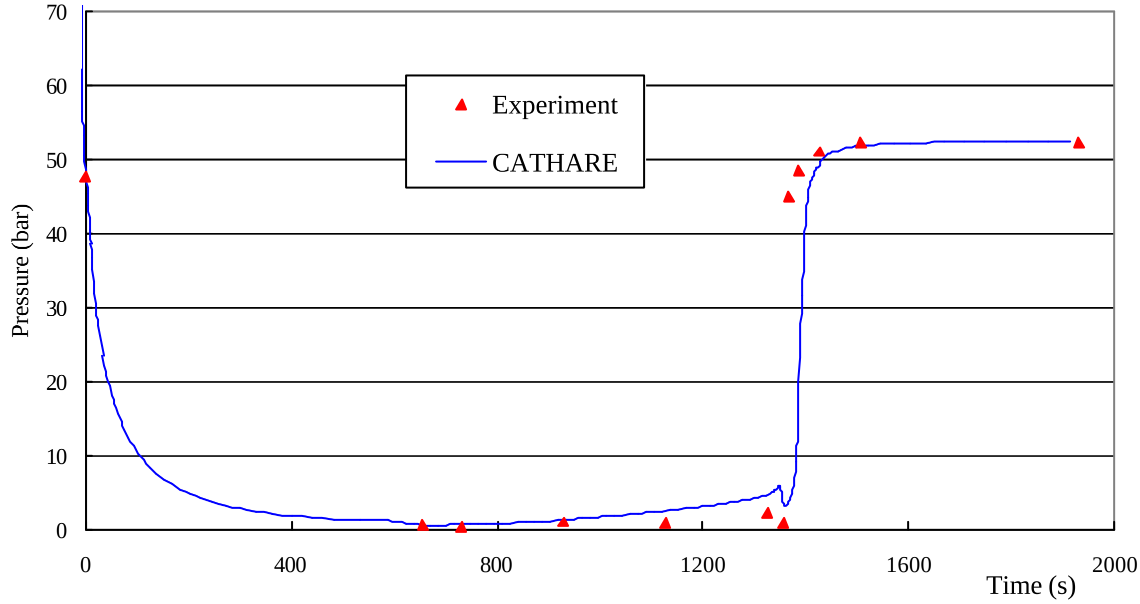


Figure 20, IETI test CMP-253 (without needle) - Pressure profile

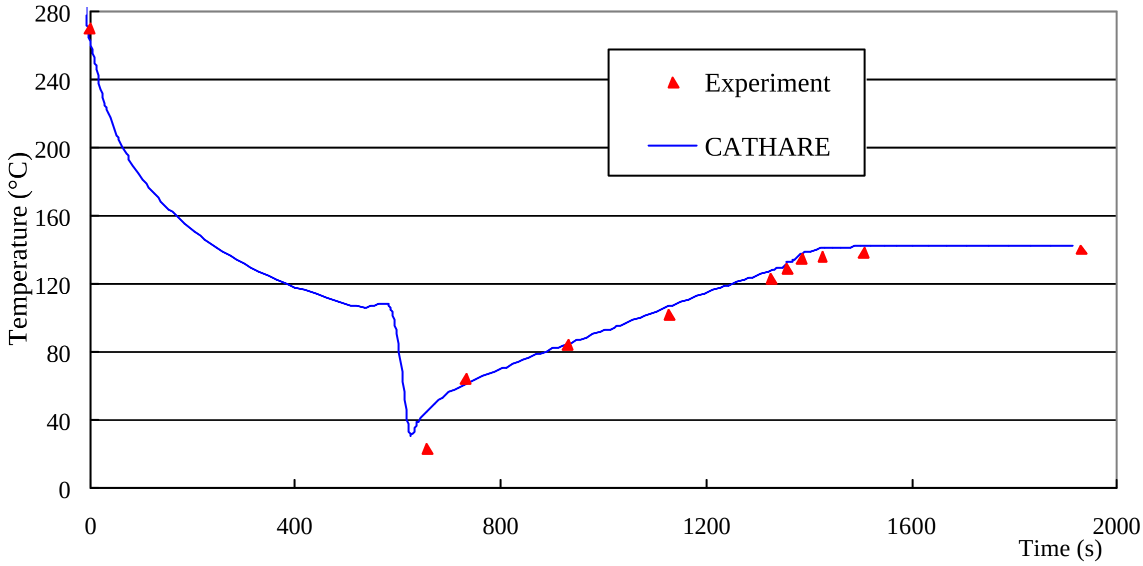


Figure 21, IETI test CMP-253 (without needle) - Temperature profile

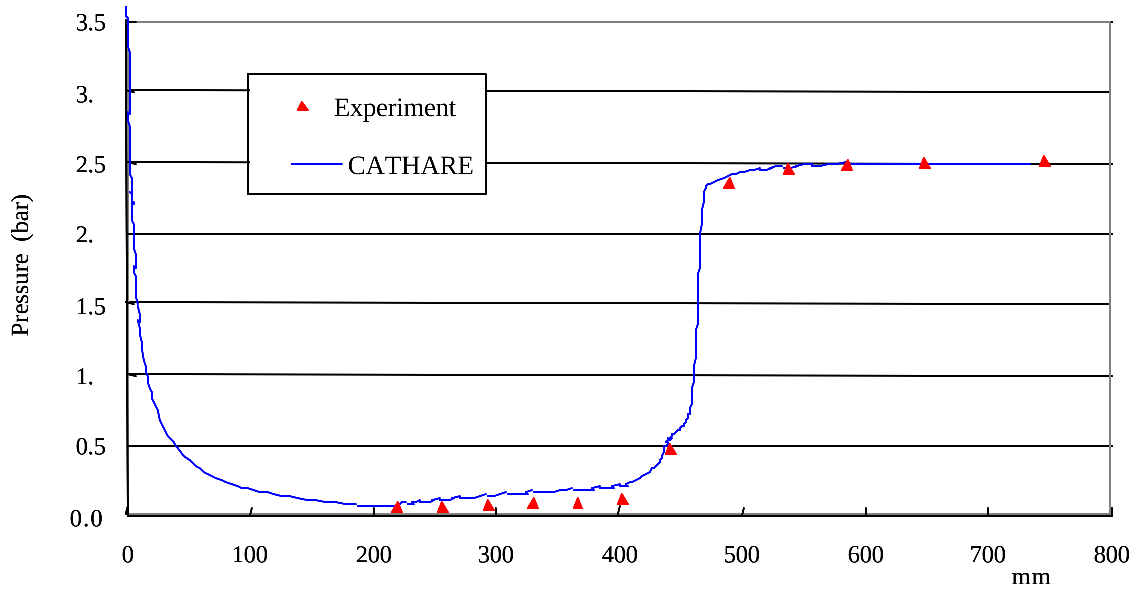


Figure 22, IMP-PAN test D07 (0.8 kg/s, 2.5 bar) - Pressure profile

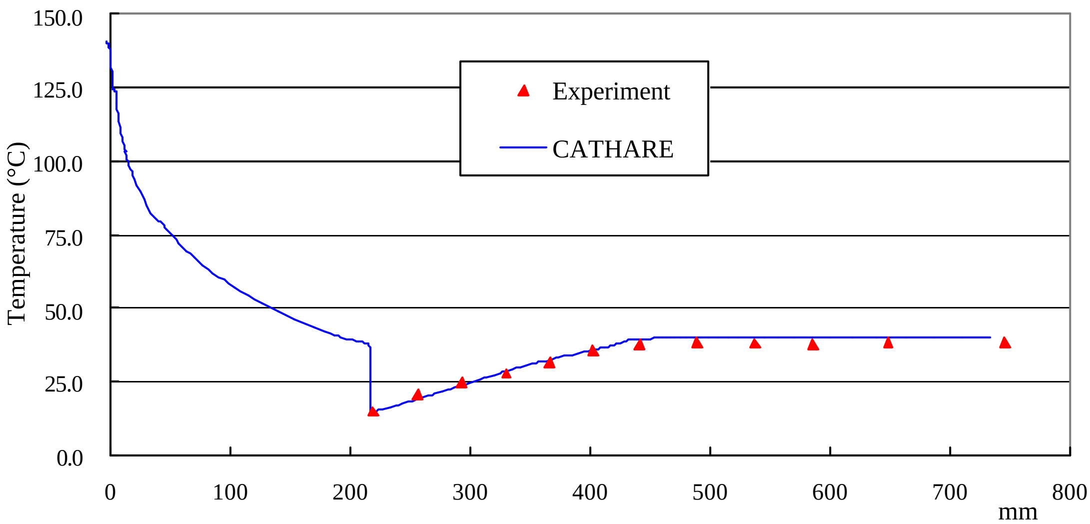


Figure 23, IMP-PAN test D07 (0.8 kg/s, 2.5 bar) - Temperature profile

5. Work Package IV- Plant calculations

The verification of the interest of a steam injector system implemented in a nuclear power plant was one of the main objectives of the DEEPSSI project. With CATHARE, one can simulate the whole PWR plant considered. including a steam generator Emergency FeedWater System based on steam injectors.

Initially, it was planned to analyze such innovative system for both the WWER-440/213 and the European Pressurized Water Reactor EPR Taking into account the experimental results, it was found out that the EPR specifications were much too demanding, then, no SI design can be proposed for this application. On the contrary, an extrapolated SI design, close to the design tested and based on CATHARE calculations, could be proposed for the WWER case. So the WWER was the only power plant considered to study a SI based EFWS. Such steam injector passive system would be used in situations where the active system cannot be used (electric power driven pumps). The typical accident of this type is the total loss of power supply : the blackout.

5.1 Simple system analyses

Before running plant calculations, a simplified EFWS circuit, with thermal-hydraulic conditions close to the WWER case, has been modeled with CATHARE (figure 24). The SI model was an extrapolated design because, using CATHARE, it was found that the different tested designs were not optimal to give the maximum back-pressure, mainly due to over-sizing of some elements.

These modifications are the following:

- a slight increase of the steam nozzle critical diameter,
- a smoother steam nozzle,
- an additional cylindrical part between the mixing chamber and the diffuser in order to get a more homogenized mixture before the condensation shock wave,
- a smaller SI length.

Unfortunately, these modifications were proposed during the late phase of the project and it was not possible to perform an experimental testing.

In initial conditions (see figure 24), the “steam generator” and parts of the feeding line and of the steam line are filled with high pressure (50 bar) saturated liquid or saturated steam, The rest of the circuit is filled with steam (to simplify the calculation, this rest of the circuit is not filled with air). Then, the injector line valve and the liquid source are opened progressively. After few seconds, the SI is in operation, the injector supplies a constant flowrate through the discharge valve at low pressure. Then, the discharge valve is progressively closed leading to the feeding line refill. When the feeding line is nearly full, the SI backpressure grows rapidly. As soon as the backpressure overpasses the steam generator pressure, the check valve opens and water is injected in the steam generator.

With a low initial water level in the steam generator, the injection of water leads to a rapid decrease of the steam generator pressure. It can be seen (figure 25) that this simplified SI system reacts quite well to such quick transient.

This simplified close circuit model has confirmed the interest of the extrapolated SI design and the CATHARE capability to combine the SI model with other types of CATHARE modules.

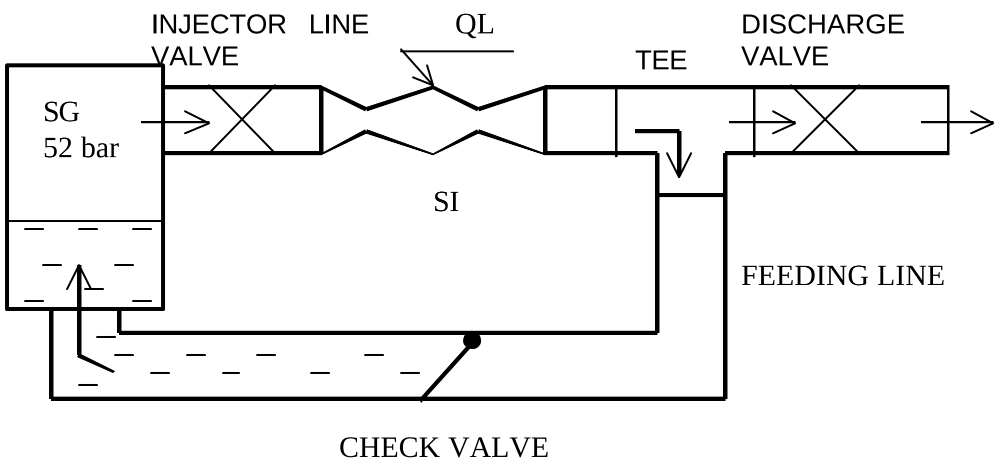


Figure 24, Schematic of the simplified SI closed system

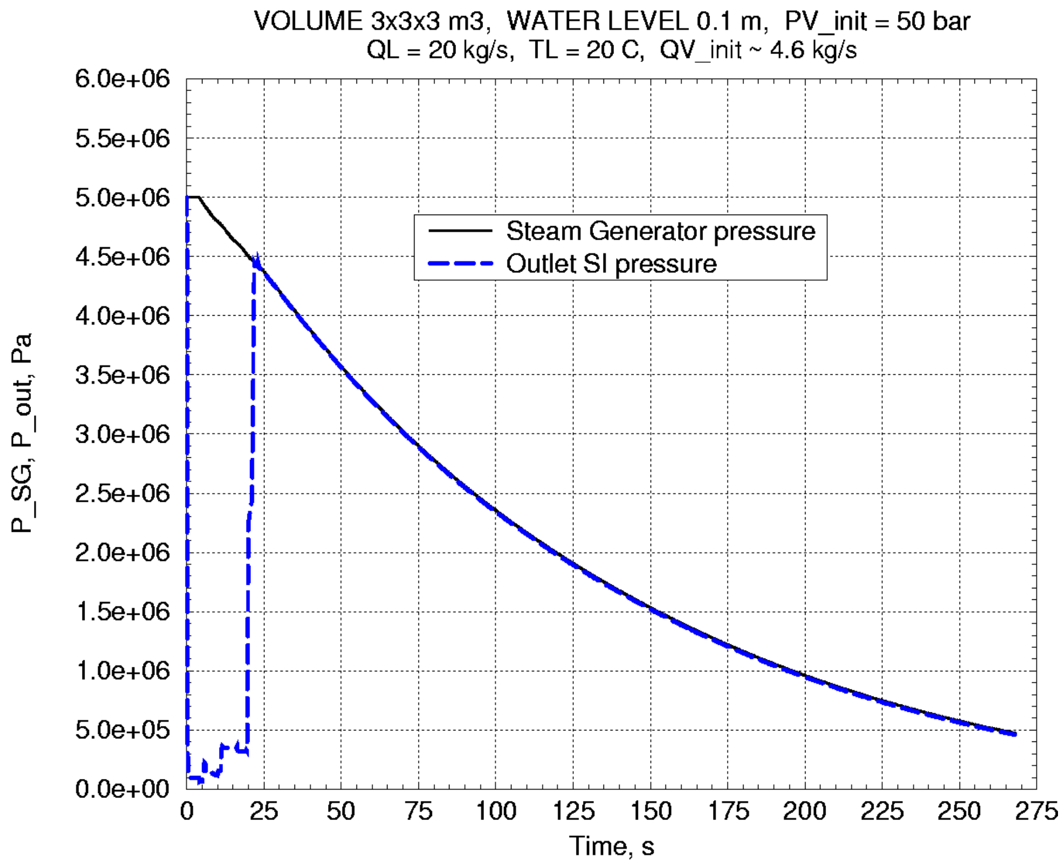


Figure 25, Simplified system calculations, Inlet and outlet SI pressure evolutions.

5.2 WWER plant calculations

The considered WWER is the Czech Dukovany power plant. In WWER, there are six main primary coolant loops. The heat exchangers between the primary and the secondary circuits are six horizontal steam generators.

The nominal operating parameters are :

- Reactor thermal power, 1375 MWth,
- Average coolant warm-up in core 30°C,
- Coolant pressure, 122.5 bar,
- Coolant flow through reactor, 39 000 m3/h,
- Steam pressure in SG, 46 bar,
- SG Feedwater temperature, 223°C,
- SG Feedwater flow, 453 t/h,
- Turbine generator electric power, 220 MW.

For the primary circuit model, an existing CATHARE model has been used. For the secondary circuit, a new CATHARE model has been developed for this project.

From practical point of view, the implementation of the SI based EFWS was done as far as possible using the existing piping and components (figure 26). Two steam injectors are used. They are implemented in the lowest possible elevation in order to have the highest water pressure at the SI inlet. They have the design presented in the previous paragraph. They suck the water stored in three tanks containing 1000 m^3 of demineralized water at a temperature of 20°C under atmospheric pressure.

The initiating event considered is a total loss of the power supply (internal and external sources, that is a blackout). Two calculations have been run, one without and the other with the SI system. After a blackout event, one has: the reactor scram, the shutdown of the main circulating pumps and the SG water feeding, the turbine trip and a fast closure of the steam line valves. The plant utilizes the accumulator electric power supply for all the essential diagnostic and control equipments.

Without the SI based system, the steam generators water levels decrease continuously (figure 27).

With the starting of one steam injector system, due to an operator action at about 550 s., the SG1 water level increase significantly. It reaches its nominal value approximately after 4000 s. Up to this time, the SI based system operates well. By the same time, the calculation is stopped.

This first calculation proved the capability of the CATHARE plant model, including a steam injector model, to simulate this type of accident. In addition, it was proven that the proposed extrapolated SI design could be used as a passive SG feedwater system for the WWER 440/213 power plants. Of course, this extrapolated design has to be experimentally validated.

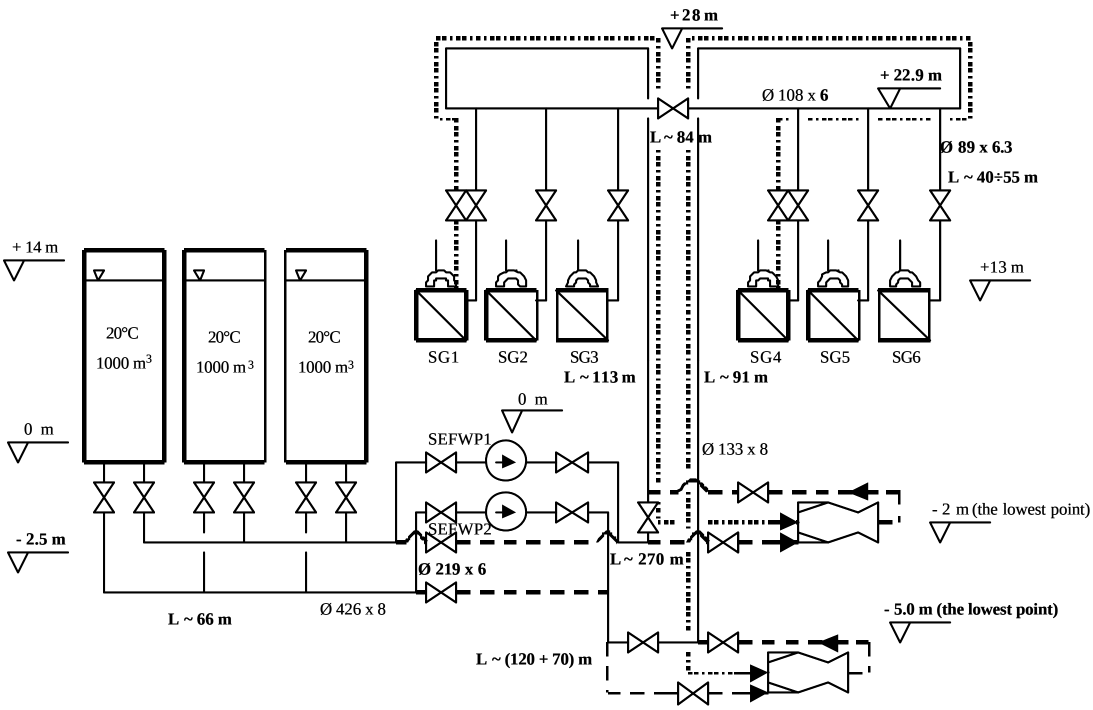


Figure 26, Schematic of the SI based EFWS, SG1 to SG6, the six steam generator, the dashed line and the dotted line are the required additional piping

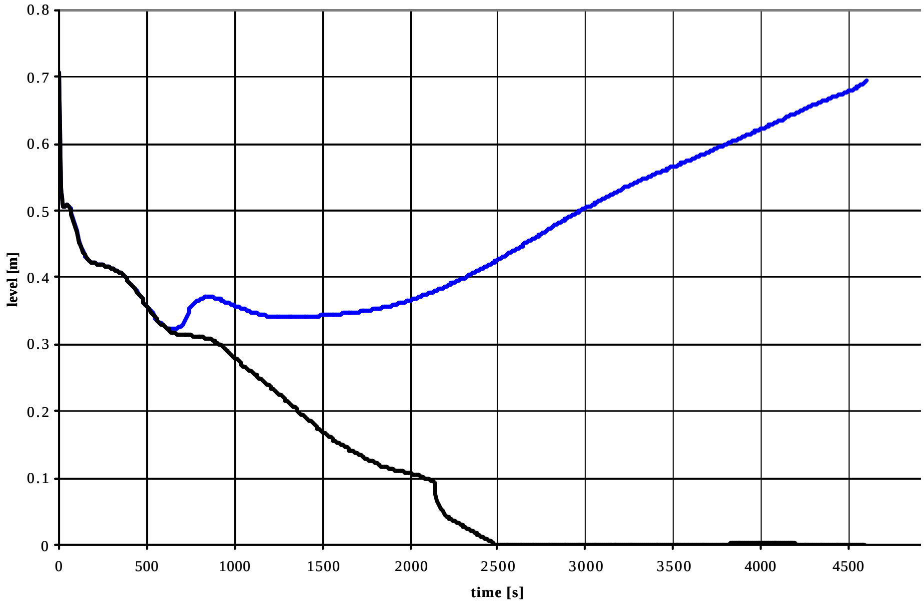


Figure 27, Steam Generator SC1 level versus time (with, blue line, and without, black line, the SI based EFWS)

6. Work Package V – Benefit evaluation

The objective of this WP was to evaluate the benefits of using a Steam injector based EFWS system in comparison with the existing solutions (especially steam driven turbine pumps). The possible benefits were :

- an increase of safety (due to an expected better reliability for a passive system),
- a reduction of the EFWS cost,
- a reduction of the maintenance needs.

To do that, It had been proposed to undertake a "PSA-like" study limited to few sequences and to use the RCM (reliability centered maintenance) method. Unfortunately, the experimental results obtained have shown that the new SI design proposed has limited performances and it cannot be used without further modifications in a real industrial system.

For the EPR case (the more demanding case), it was not possible to propose a SI design without further studies (including experiments). It was therefore impossible to undertake an useful benefit evaluation without a realistic system layout.

For WWER applications, an extrapolation of the tested design has been proposed and, some CATHARE calculations have shown that this extrapolation was reasonable. A system layout has been proposed (WP4) for a supplementary EFWS system. Some preliminary CATHARE calculations of this system have been performed. However, most of the useful data of the WWER plant studied in WP4 were restricted by industrial property considerations, so they could not be transmitted to CESI in charge of WP5. This latter difficulty had not been identified during the project preparation. Finally, taking into account the preliminary nature of the WWER proposed design, it has been decided by the project partners to don not undertake WP5 studies.

7. Conclusions

The main objective of the DEEPSSI project was to design and test innovative steam injector designs. The CLAUDIA and IETI tests have demonstrated that the considered options lead to a more efficient steam injector. For steam injectors with annular water injection, central steam injection and no overflow in the mixing chamber, a significant performance improvement has been obtained.

For WWER applications, an extrapolated SI design has been proposed. An experimental program will be necessary to have an industrial qualification of these proposals. For more demanding applications (like in the EPR conditions), more revolutionary design should be proposed for a single-stage steam injector, an alternative is to study the possibility of combining two apparatus in order, for example, to increase the pressure in two steps.

As far as the model development is concerned, the CATHARE capabilities, regarding steam injector modeling, have been confirmed. There are still some studies to conduct in order to have a model with better predictive capabilities, especially if other steam injector types are considered (with central water injection for example).

The SI CATHARE model of the extrapolated SI design has been used in a complex WWER plant input data deck. A quite satisfactory behavior of this complex model has been obtained calculating a blackout accident.

The DEEPSSI project has been a successful collaboration, even if the SI design tested was not as good as expected. The DEEPSSI partners are now analyzing very carefully all these results obtained in order to evaluate the interest to launch a complementary program.

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Nomenclature

P_{v0} inlet steam pressure
P_{l0} inlet water pressure
Q_{vo} inlet steam flowrate (kg/s)
Q_{l0} inlet water flow rate (kg/s)
T_{l0} inlet water temperature
P_{sat} saturation pressure
T_{sar} saturation temperature
T_V local steam temperature
T_L local water temperature
V_V local steam velocity
V_L local water velocity
α local void fraction
ρ_V local steam density
D_H hydraulic diameter
q_{le} : liquid-to-interface heat flux (W/m^3)
τ_i interfacial friction coefficient (N/m^3)
a_i interfacial area (m^2/m^3)