INSTRUMENTING FULL-SCALE BORON INJECTION TEST FACILITY TO SUPPORT ATUCHA-2 NPP LICENSING

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ABSTRACT

The Atucha-2 Pressurized Heavy Water Reactor is equipped with a back-up shutdown system based on the fast injection of boron into the moderator tank. Such system had initially been designed to cope with a 10%-area (0.1A) break Loss Of Coolant Accident (LOCA) scenario, but based on upgraded licensing requirements the design had to be revised and possibly improved against a double-ended guillotine (2A) break LOCA. In particular, the boron injection had to be proven fast enough to allow a timely shutdown of the reactor, even in the case of a failure of the primary shutdown system (control rods).

A full-scale test facility was built for such "design validation" purpose, in the framework of a cooperation program between the University of Pisa – San Piero a Grado Nuclear Research Group (GRNSPG) and the utility Nucleoeléctrica Argentina S.A. (NA-SA). A special instrumentation system, based on conductivity probes designed on purpose by the Helmholtz Zentrum Dresden-Rossendorf (HZDR), was adopted for the measurement of the injection delay, as well as for the monitoring of pressure at several key locations. Care was taken to reproduce the relevant NPP conditions as closely as possible to those expected on the basis of extensive safety analyses performed adopting a Best Estimate Plus Uncertainty (BEPU) approach. In this respect, not only the test facility is full-scale, but also the key components (such as the fast opening air valves, the boric acid tanks, the rupture device, the injection lance) were directly borrowed from the Atucha-2 NPP.

The experimental campaign carried out by NA-SA on such test facility allowed to improve the design of the boron injection system (especially as to some fluid-structure interaction issues) and finally to achieve the main goal, i.e. the demonstration that the system's performance is fast enough to assure a timely and safe shutdown of the reactor. This was a key contribution to the successful completion of the NPP licensing process.

KEYWORDS
ATUCHA-2, CONDUCTIVITY PROBES, FAST BORON INJECTION, FULL-SCALE, LICENSING, LOCA

1. INTRODUCTION

The Atucha-2 Pressurized Heavy Water Reactor (PHWR) Nuclear Power Plant (NPP), designed by Siemens/KWU, came into commercial operation in 2014, after a long and troubled story started when the plant was ordered in 1979, the construction work then being slowed down and even suspended for a long time due to financial and political issues.

Safety analyses aimed at the NPP licensing were carried out by specialists of the San Piero a Grado Nuclear Research Group (GRNSPG) of the University of Pisa (UNIPI), in the framework of a collaboration agreement with the utility Nucleoeléctrica Argentina S.A. (NA-SA), in the period 2007-2013. In particular, a pool of state-of-the-art computer codes was adopted, following a Best Estimate Plus Uncertainty (BEPU) approach, to simulate the plant behaviour during a set of postulated accidental scenarios and demonstrate that the prescribed safety requirements were met (see for instance Refs. 1 and 2). The outcomes of those analyses constituted the Chapter 15 of the Final Safety Analysis Report (FSAR), which was provided to NA-SA by the Italian team and then submitted to the Autoridad Regulatoria Nuclear (ARN, the Argentinian nuclear safety authority).

Concerning the postulated accidents, and particularly those induced by Loss of Coolant Accidents (LOCA), the Atucha-2 reactor had been originally designed to withstand a “0.1A-break”[1] LOCA as the most severe case. However, based on upgraded licensing requirements recently prescribed by the Safety Authority, the NPP safety had then to be demonstrated against up to the double-ended guillotine (“2A”) break LOCA, which constituted quite a big challenge.

This implied also a revision of the design of the reactor back-up shutdown system, which relies on the fast injection of a boric acid solution into the in-vessel moderator tank: it had to be proved that the injection is fast enough to timely and safely turn the reactor power down in case of a 2A-break LOCA. In this respect, experts from both sides agreed upon the need to perform experimental tests so as to avoid relying on analytical predictions only.

In addition to the various collateral activities[2] that were performed by UNIPI in the frame of the above-mentioned collaboration, a new task was undertaken to support the design, construction and operation of a test facility that reproduced the fast boron injection system (described in Section 3 and 2 respectively) and its key operating conditions in the event of a 2A-break LOCA, and allowed a direct measurement of the injection delay. The latter would then be used as a reference for safety assessment purposes.

Key features of the Boron Injection Test Facility (BITF) are:

- being full-scale;
- the utilization of original key components (such as the fast opening air valves, the boric acid tanks, the rupture device, the injection lance) directly borrowed from the NPP;
- the adoption of an injection delay measurement system (supplied by UNIPI) relying on the detection of boron front arrival by means of conductivity probes.

The BITF experimental campaign was conducted in 2011-2012 and fully met the intended goals: the injection delay was measured in a number of different situations reflecting possible variations of operating parameters, and the obtained information was then used to support the assumptions made in the licensing analyses.

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[1] I.e. a LOCA induced by a cold leg break whose area is 10% of the cold leg cross sectional area.

[2] Extra studies to further substantiate the reactor safety analysis were carried out by UNIPI. For instance, CFD simulations were performed to investigate several aspects of the fast boron injection process, such as the boron distribution inside the moderator tank (e.g. Refs. 3, 4, 5), the pressure drops through key components (e.g. Ref. 5, 6), etc.

2. THE ATUCHA-2 NPP FAST BORON INJECTION SYSTEM

2.1. Description of the System

The Fast Boron Injection System (usually referred to by the German acronym JDJ, and sketched in Figure 1) is constituted by four independent injection lines, each of which includes the following key components:

- a 1 m^3 air accumulator, kept at a pressure of 220÷230 bar;
- two syringe-like tanks, about 145 dm^3 each, filled with a boric acid water connected to the air accumulator by a pipe (with a tee to allow the arrangement in parallel)[3];
- two normally-closed quick-opening air valves (opening time in the order of few tens of milliseconds) respectively located on the two pipes between the boron tanks and the tee (as close to the tanks as possible); the two pipes downstream of the valves are interconnected by a horizontal pipe, which stabilizes the behaviour of the system against the effect of possible asymmetries;
- a Rupture Device (RD) located on the piping that connects the boric acid tanks to the Reactor Pressure Vessel (RPV), which in normal conditions faces the reactor conditions (full pressure, hot non-borated water) on the downstream side and borated water at atmospheric pressure and temperature on the upstream side; the pressure boundary is constituted by a thin stainless steel membrane resting on a thick perforated stainless steel block, which acts as a “vacuum support” against the reactor pressure (as long as the JDJ system is idle); when the Δp is inverted, and large enough, nothing prevents the membrane from bursting; a strainer faces the membrane and, in the case of its rupture, prevent the fragment to be transported to the RPV; see Figure 2;
- an injection lance (Figure 3), which constitutes the end part of the piping downstream of the RD and is designed to allow the injected solution to effectively spread inside the moderator tank (which, in turn, is located inside the RPV); the overall length of the lance is about 5.5 m; the terminal part is formed by two coaxial Zircalloy pipes (the inner one protruding beyond the end of the outer one), both having two longitudinal rows of small holes drilled on opposite sides, and the inner one having also a larger central hole at its end; the rest of the lance is formed by a straight stainless steel pipe sized approximately as the above outer pipe; the four lances are arranged as shown in Figure 4 (left) with respect to the moderator tank; they are tilted at 25° with respect to the vertical direction, and are not aligned with the RPV centreline.

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[3] The dynamics of the tank piston is not only relevant to the injection delay, but also to the structural mechanic integrity of the JDJ system: when the pistons hit the bottom of the tanks they stop abruptly and thus generate a pressure transient (waterhammer), which potentially leads to unacceptable loads. A CFD assessment was made by NA-SA specialists (Ref. 7), which brought to the identification and implementation of modifications of the piston design, in order to smooth the breaking process and thus noticeably reduce the pressure peak loads.

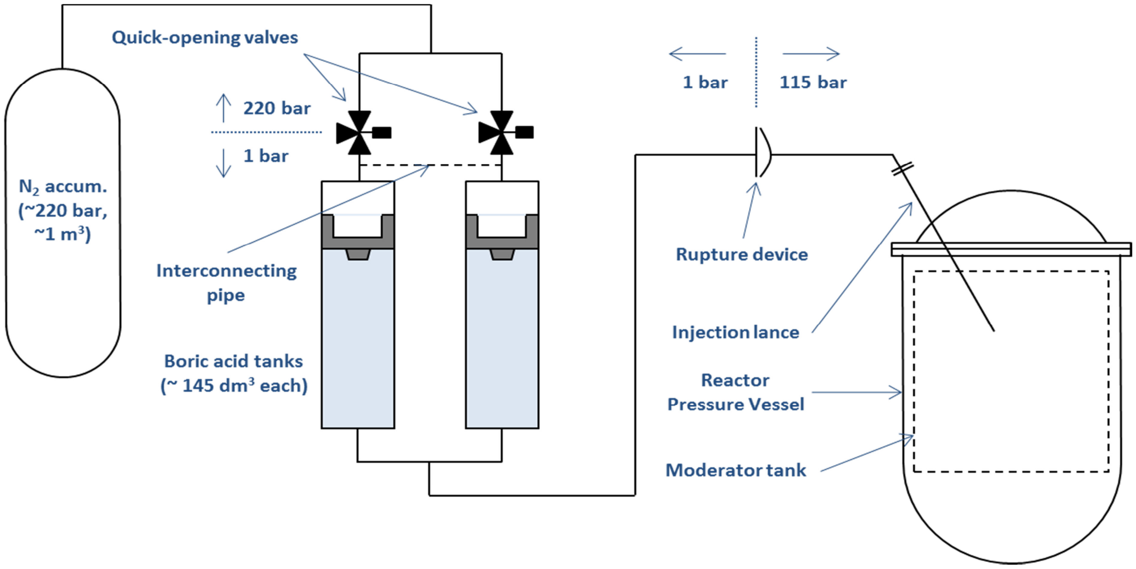

Figure 1. Sketch of the JDJ system.

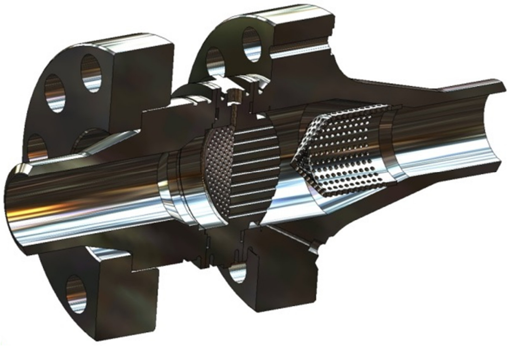

Figure 2. Cross sectional CAD view of the RD.

Figure 3. CAD view of the terminal part of the injection lance.

In the case of a LOCA event, the NPP Instrumentation and Control (I&C) system commands - among other safety and protection functions - the opening of the above two valves; as they start to open, a rapid pressurization of the whole line down to the rupture device occurs; as soon as the pressure upstream of the RD exceeds the reactor pressure by a certain threshold amount (estimated to be about 20 bar) the RD membrane bursts and the borated water starts flowing toward the RPV; the boron will reach the moderator tank after displacing the non-borated water contained in the piping downstream the RD and inside the injection lance.

Figure 4 centre and right parts refer to two different instants during an injection transient, as predicted by a Computational Fluid Dynamics (CFD) simulation, and show how the borated water spreads out of an injection lance forming a sort of "clouds", larger and larger as the injection proceeds.

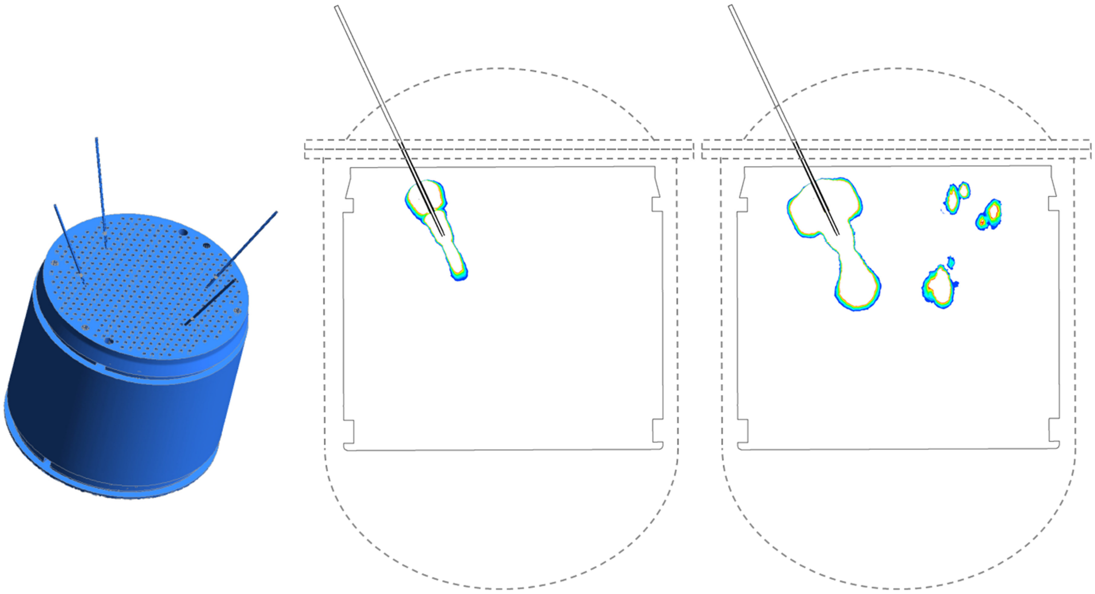

Figure 4. Injection lances arrangement (left); CFD-simulated boron clouds at two different instants of an injection transient – vertical cross-section of one lance (centre and left images).

The injection and diffusion of the borated water causes an insertion of negative reactivity, which is sufficient to shut the reactor power down even if the primary shutdown system fails to insert the control rods. However, if the process is not rapid enough, the uncooled fuel can experience excessive temperature excursions and hence be damaged. Quantifying the delay affecting the boron injection is thus essential.

2.2. Injection Delay

The overall boron injection delay, with respect to the occurrence of the initiating event (e.g. the cold leg break), is the result of several contributions, associated with the following processes:

(a) detection of the accident and generation of a shutdown signal (by the NPP I&C system);
(b) actuation of the JDJ quick-opening air valves (governed by the operation of a set of pilot valves, pneumatically actuated);
(c) JDJ valves' stems rising;
(d) air flow through the valves and pressurization of the boric acid tanks (and of the whole injection line down to the RD) until the threshold Δp is reached;
(e) RD membrane burst;
(f) flow of the borated water through the several meters distance between the RD and the moderator tank;
(g) diffusion of the borated water inside the moderator tank.

The origin of the contribution (a) does not pertain to the JDJ system and so is outside the scope of the experimental investigation.

During the normal operation, the pilot valves (four for each air valve) are kept closed by an excitation current flowing through their coils, and this causes the pneumatic actuator of the air valves to stay in the closed position. The air valve opening is commanded by switching a relay which cuts the excitation currents, thus causing the pilot valves to open, and the pneumatic actuator of the air valves to open as well (pushed by the now non-contrasted internal air pressure). This process takes a finite, though small, time (contribution b). The relay switching (hence, the pilot valves de-excitation) is assumed as the reference event with respect to which the injection delay is measured.

The valves opening time (contribution c), for which a nominal value was available from the manufacturer's data sheets, turned out to be a particularly uncertain parameter: NA-SA specialists analyses had shown in fact that possible chocking phenomena at the valve throat, complex pressure transients induced by the fast opening, combined with the particular 3-way configuration of the valves themselves, could delay the stem rise (Ref. 8).

Also the time needed by the RD membrane to break was a priori unknown, both because of the uncertainty on the threshold Δp and because, even once the limit is reached, the membrane takes a finite time to rupture.

The time the borated water takes to reach the moderator tank (contribution f), once the RD membrane has broken, mainly depends on the overall pressure drops encountered by the flow: the larger the flow resistance, the smaller the flow rate, the longer the time. This is a major contribution and indeed NA-SA adopted some design modifications, with respect to the original design, to reduce the pressure drops (e.g. larger pipe, larger RD, etc.) Estimation of such losses, e.g. for rupture device and injection lance, were obtained both by UNIPI and NA-SA by CFD calculations (Refs. 5, 9).

Also contribution (g) is not directly related to the performance of the JDJ system itself, but rather on to the thermal-hydraulic behaviour of the borated water as it spreads out of the injection lances. All the other contributions do instead characterize the performance of the injection system and can only empirically be quantified.

3. THE BORON INJECTION TEST FACILITY (BITF) AND ITS INSTRUMENTATION

3.1. General Description

The Boron Injection Test Facility (BITF) was designed and built by NA-SA, upon recommendation by - and with scientific and technical support from - UNIPI, with the purposes of directly measuring the boron injection delay in operating conditions as close as possible to the actual NPP conditions (during the scenarios of interest), and identifying possible design improvements for the JDJ system.
The facility (a CAD representation of which is given in Figure 5) was conceived since the beginning as a full-scale almost exact replica of the JDJ system, since any scaled or geometrically changed configuration would have introduced further sources of uncertainty and thus impaired the outcome of the project.

For the same reason, the following original components were borrowed from the NPP, instead of using similar components supplied on purpose:

- air accumulator;
- quick-opening air valves;
- boric acid tanks;
- rupture device;
- injection lance.

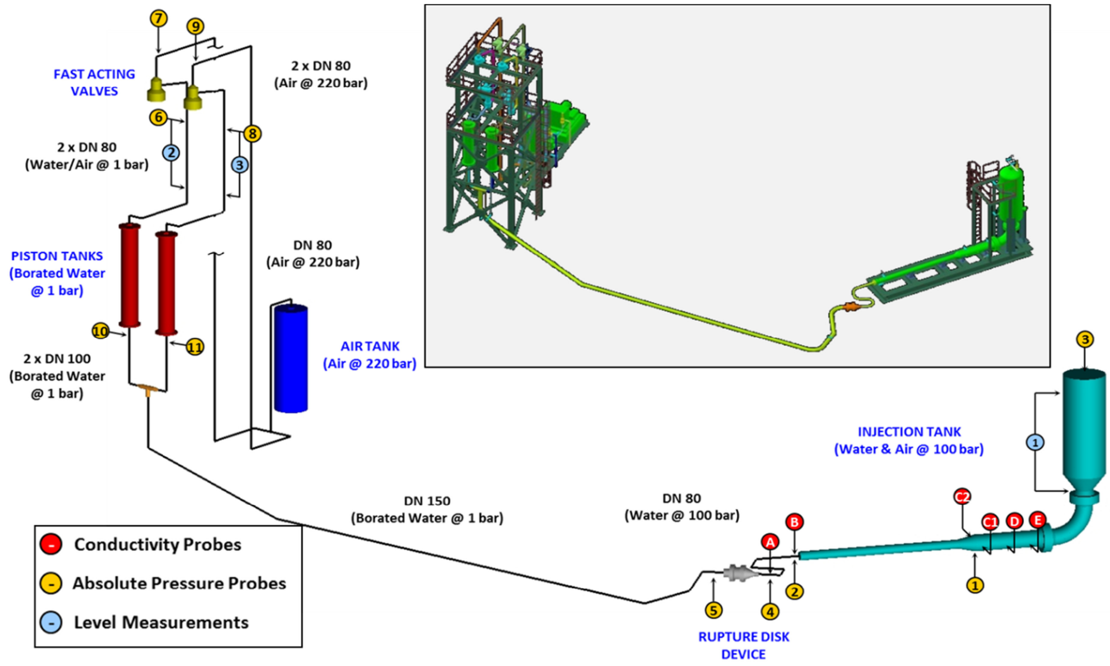

Figure 5. CAD overall view of the BITF with UNIPI-supplied instrumentation.

The piping that connects such components was designed so as to reproduce the actual geometry and layout of one of the four trains of the JDJ system[4], with some exceptions that are described hereafter. The elevations in the air piping between the accumulator and the valves deviate from the real system, so as to achieve a more compact layout; due to the high absolute pressure, the errors associated with the hydrostatic contributions are negligible.

A full-scale RPV / moderator tank assembly could obviously not be reproduced, as its costs would have exceeded by orders of magnitude the value of the project; instead, an injection tank was used, designed to host the injection lance, to be kept at reactor pressure conditions (about 100 bar, during the relevant phase of the postulated LOCA scenario, when only a limited depressurization has occurred) and to receive the whole amount of injected water. The injection tank is shaped as a (smoking) pipe: the horizontal part is filled with water, hosts the injection lance and, in the larger-diameter section, receives the injected solution; the vertical large-volume part is mostly filled with air (at the target reactor pressure conditions) and accommodates for the water level increase during the injection. Such arrangement requires the injection lance to be oriented horizontally, instead of being tilted by 25° with respect to the vertical direction as in the JDJ system: this is a negligible deviation from the reference design, since the lance orientation determines negligible hydrostatic contributions to the overall pressure losses, and allowed to keep the BITF layout relatively simple and compact.

The water level rise in the injection tank determines a pressure increase which opposes to the injection itself and brings to a larger delay than it would be achieved in a more realistic constant-pressure system. However, such pressure increase is limited to a few bars until the boron reaches the

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[4] Reference was not made to the original design, but rather to an improved design recently developed by NA-SA in order to reduce the pressure losses. The four trains are almost identical, the differences being not relevant to the scope of the experimental investigation.

moderator tank (approximately, the first 0.5 s), then it reaches up to a few tens of bars until the end of the injection (about 3-4 s). The effect on the injection delay estimation is negligible.

The BITF piping layout has minor differences with respect to the JDJ system, with no impact in terms of pressure losses.

3.2. Instrumentation

One of UNIPI's tasks was to design and supply the instrumentation and data acquisition systems (DAS) for the fast measurements which the experiment was intended for (NA-SA being in charge of the rest of the I&C system), particularly for:

1. detection of the "boron arrival" into the injection lance (and hence measurement of the injection delay, which was the main target of the experiment);
2. measurement of the gauge pressure during the injection transient at key locations (useful for thermal hydraulic and structural assessment purposes);
3. measurement of water level in the vertical part of the injection tank and in the pipes that connect the air valve to the boron tanks (off-line low-pressure measurements during test preparation; not addressed further in this paper).

3.2.1. Conductivity probes

The solution proposed and agreed upon for the detection of the boron arrival was the use of electrical conductivity probes to be placed at six key locations close to the injection lance and along the injection line: the presence of boron alters the water conductivity and can thus be easily detected. Basically, an ON/OFF signal is sufficient for the purpose, while it is not necessary to measure the boron concentration. However, the concentration measurement constitutes an "added value", as it can turn useful for boron mixing assessment, thus the decision was made to use probes capable of measuring the boron concentration.

The HZDR was selected as the supplier for the probes, owing to their wide experience with this type of instrumentation. The following main tailored-design specifications were agreed upon:

- electrical conductivity range: 0 – 40 µS/cm;
- stainless steel;
- design pressure 300 bar (which, based on thermal-hydraulic analyses, accommodates the pressure peak experienced in the injection line immediately after the RD opening, after which the pressure tends to stabilize between the initial pressure of the compressed air and the initial pressure of the injection tank);
- design temperature 25 °C;
- frequency ≥ 1 kHz (i.e. measurement every ≤ 1 ms → this is approximately the error that will affect the injection delay measurement);
- sheath outer diameter 10 mm;
- probe length 30 cm;
- mechanical interface to the system: bored-through compression fitting (Swagelok).

As shown by the drawings and photos in Figure 6, the sensor is constituted by a couple of electrodes, namely a metal wire and a coaxial metal tube, divided by a thin layer of electrical insulating material; at the probe tip the inner wire is protruded by a few millimetres beyond the tube electrode. The sensor is inserted into a thick stainless steel pipe (i.e. the outer sheath), which serves as a structural support for the sensor and makes the design particularly rugged. The other end of the device (right side of both drawings and bottom photo in Figure 6) contains the electrical terminals, and - once the probe is installed - is found outside of the pressure boundary. The nut at the base of the sheath is to be tightened to a compression fitting welded on the BITF piping or injection tank.

The black box shown in the top photo contains the data acquisition electronics associated with the probe: it provides electrical excitation to the probe (10 kHz trapezoidal voltage pulses), conditions and processes the response current signal generated by the probe, and provides an analogue voltage output signal (0 – 5 V_{DC}), which is then received by the general DAS (see section 3.2.3).

The conductivity probe electronics was also provided by HZDR, the design being adapted from previous similar probe designs to meet the present specifications.

The six conductivity probes were arranged as follows (Figure 7):

- A: immediately after the RD (not shown in the Figure);
- B: immediately before the injection lance flange (i.e. about 5.5 m from the lance end);
- C1 and C2: in front of the “first hole” on the outer pipe of the lance (both sides; only one shown in the Figure));
- D: in front of the “first hole” on the inner pipe of the lance;
- E: in front of the lance end (probe tip reaching the lance centreline).

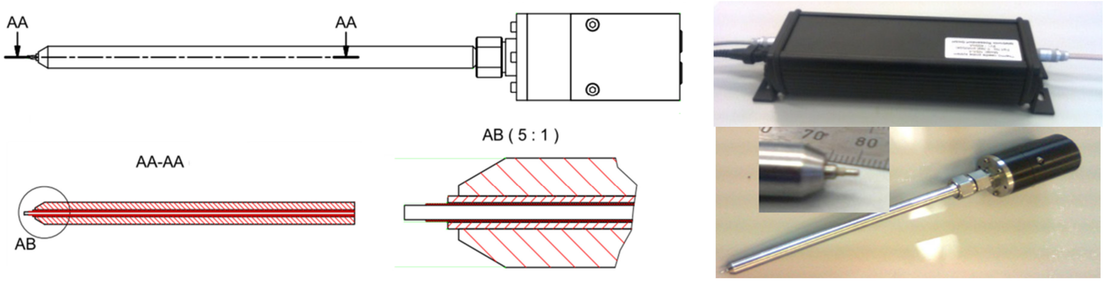

Figure 6. Conductivity probe.

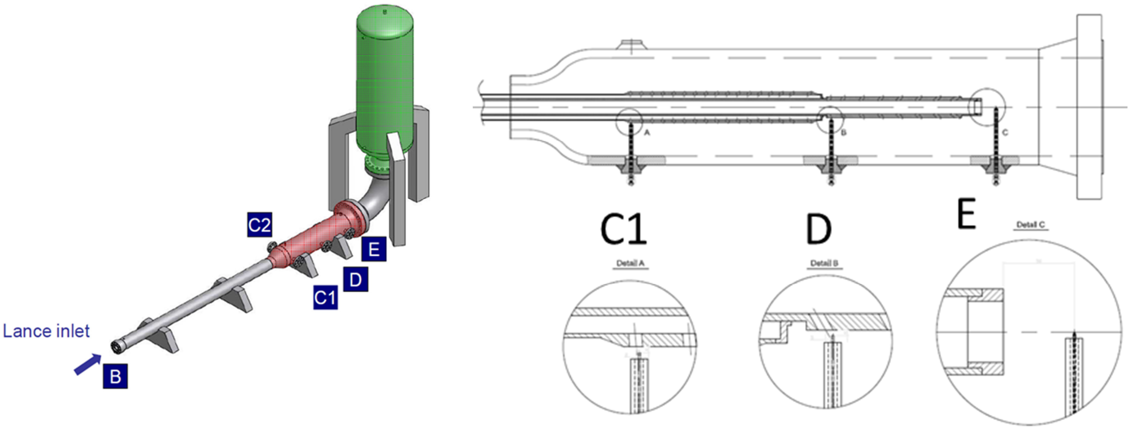

Figure 7. Arrangement of conductivity probes.

The above arrangement allowed multiple approaches to the characterization of the boron front arrival, although the most significant information is that provided by probes C1 and C2 (which also explains the redundancy).

Care had to be taken, both in the design and in the installation phases, to assure the appropriate positioning of the tips of probes C1, C2 and D. In fact, the tips must be close enough to be fully intercepted by the borated solution as it exits from the holes and before it undergoes any mixing, but must not be so close as to plug the holes; a rather precise alignment is necessary (within about 1 mm), and the inclined orientation of the holes (especially D) must be taken into account, as well as the actual “stretched” geometry of the injection tank when pressurizes (which affects the relative positioning of probes and lance).

A structural mechanic assessment was necessary to guarantee that the transvers hydraulic forces acting on the probes during the injection would not lead to excessive bending and impair the structural integrity. This task was performed by means of CFD simulations (for hydraulic forces estimation) and finite element analysis (for mechanical assessment).

A preliminary calibration of the conductivity probes was performed at UNIPI laboratories at ambient pressure and temperature conditions. An on-site calibration, with all the probes installed on the BITF at their respective locations, would then have been necessary in order to obtain accurate boron concentration measurements; however, for practical reasons no on-site calibration was performed and the probes output signals were regarded as ON/OFF information only (which is sufficient for the purposes of the tests, i.e. the boron detection).

3.2.2. Pressure sensors

The instrumentation system included 11 gauge pressure sensors located at the following positions:

- upstream of air valves (CP007 and CP009);
- downstream of air valves (CP006 and CP008);
- downstream of boric acid tanks (CP010 and CP011);
- upstream of RD (CP005);
- downstream of RD (CP004);
- injection lance inlet (CP002);
- injection tank – horizontal section (CP001);
- injection tank – top of vertical section (CP003).

The pressure measurement were necessary to characterize the hydraulic and mechanical behaviour of the injection system during the intense pressure transient induced by the quick opening of the air valves as well as by the burst of the RD membrane. For this purpose, fast, accurate and robust pressure transmitters were required. IMPRESS IMP industrial pressure transmitters were selected; they have a piezo-resistive ceramic sensor in a stainless steel housing, and minimal electronics based on a Wheatstone bridge; the accuracy is as good as 0.1% of full range, the response time is 0.2 ms, the output is a DC voltage in the range of few millivolts.

The pressure transmitters were installed directly on the BITF pipes and components, avoiding any interfaces that could possibly damp the signals (see example in Figure 8). It was necessary to protect the weak output signals from electromagnetic disturbances by proper cable shielding, optimal earthing and configuration of the DAS.

3.2.3. Data acquisition system

All the signals from the conductivity probes and the pressure transmitters, as well as those from the transmitters of the air valves' stems position and of the pilot valves excitation status[5] were acquired and stored by a dedicated DAS. DEWESOFT® products "DEWE 101" and "DEWE 43" (main and expansion units, resp.), shown in Figure 9, were selected for the purpose: they feature a rugged and compact design, sufficiently high performance in terms of sampling rate (up to 200 kHz) and resolution (up to 24 bit), analog inputs with different voltage configurable ranges, an embedded CPU and a solid state memory drive for handling all data acquisition, processing and storage functions on-site, very easy configurability and user-friendly graphical interface for the set-up of a control and monitoring panel (either locally or on a remote PC).

During the experiments the acquisition rate was set to 5 kHz, a compromise between the requirement of a sufficiently dense sampling and the need to limit the amount of data to store and process.

The DAS units were placed in the BITF warehouse, as close as possible to the instrumentation. For safety reasons, all control and monitoring operations were performed in an external room, by means of a PC communicating with the DAS via an Ethernet connection.

Figure 8. Pressure transmitter installed on piping upstream of one air valve.

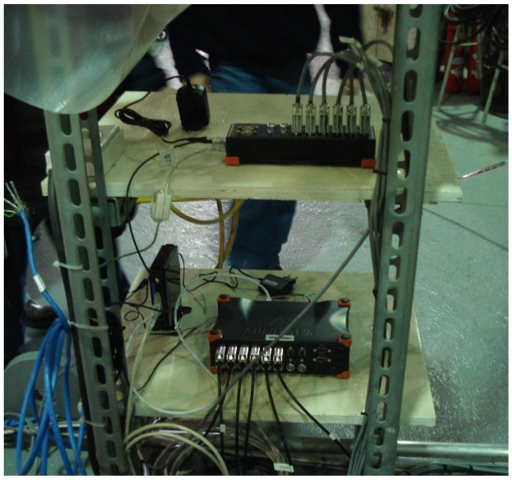

Figure 9. DAS units during installation: DEWE 101 (bottom) and DEWE 43 (top).

3.2.4. Injection delay measurement uncertainty

The "injection delay" is defined in the present context as the time spanning between two events: the fall of the current flowing in the pilot valves' coils, and the first detection of boron inside the expansion tank.

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[5] The measurement was performed by means of magnetic field sensors based on Hall Effect, developed on purpose by NA-SA, which provided an indirect measure of the flowing current. As mentioned before, the change of state of this signal constitutes the "time zero" of the injection process.

The detection of the first event is based on a current transient (from "current in the coils" to "no current"), the duration of which was shown, by specific laboratory tests, to be ranging between 50 and 110 µs. Such transient cannot be resolved by a 5 kHz sampling rate (i.e. every 200 µs). If t_0^{meas} is the last sampled time for which a full excitation is measured before the current drops (see Figure 10) and $\Delta = 200\mu s$ is the sampling period, then the valve opening is expected to start within the time interval $[t_0^{meas},\ t_0^{meas} + 2\Delta]$. t_0^{meas}can conservatively be assumed as the reference "zero" time, with an associated error equal to $2\Delta = 400\mu s$ (on the "plus" side).

Likewise, the "boron arrival time" t_1^{meas}, is arbitrarily assumed as the first sampled time at which an appreciable increase (larger than the background noise) in the output voltage of either probes C1 or C2 is observed. The associated error is $\Delta = 200\mu s$ (on the "minus" side).

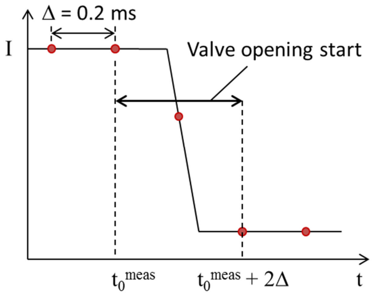

Figure 10. Identification of reference zero time.

Overall, the error affecting the injection time measurement, associated with the DAS sampling rate, is less than 1 ms. That is a relatively small contribution, compared to the other sources of uncertainty (which, overall, were estimated to amount to something in the order of 10 ms):

- compressed air pressure (variability of a few bars);
- valve opening time (variability of a few milliseconds);
- position of the boron tanks pistons (variability of a few centimetres);
- RD opening threshold pressure (variability of a few bars);
- pressure losses associated with the open RD (variability of geometrical configuration of the broken membrane – not characterized);
- discharge tank pressure (variability of several bars).

The experimental campaign involved a rather limited number of tests (about ten), each with a different configuration, thus no statistical information on the experimental uncertainty could be directly obtained. Instead, an uncertainty analysis was numerically performed by NA-SA by means of a Monte Carlo-like methodology involving statistical RELAP5 simulations coupled to pressure transient simulations (by a Method-of-Characteristics-based in-house code), the codes and models having been previously validated against the available experimental data.

The methodology and the outcomes of the analysis are described in NA-SA internal reports (e.g. Ref. 10). Basically, many coupled calculations are performed (with randomly varied set of input parameters, according to known or expected distributions around reference values) and the maximum of the predicted injection delays is picked. The number of calculations run is sufficiently large to guarantee a 95% probability that a 95% confidence level is achieved.

4. OUTCOMES OF THE EXPERIMENTS

About ten main tests were conducted, which featured different system configurations, the varied parameters being: air accumulator initial pressure; injection tank initial pressure; position of pistons; water level above the boron tanks pistons; characteristics of rupture membrane. Boron injection delay and gauge pressure measurements were performed for all tests. In particular, injection delays ranging between 366 ms and 560 ms (depending on the configuration) were measured.

The campaign was preceded by several preliminary tests, aimed at checking the operability of the test facility and optimize the configuration of the I&C system.

Some results of one of the preliminary tests are reported hereafter for illustrative purposes. Not all test operating parameters are consistent with the final reference conditions; therefore the results shown are not quantitatively relevant to the objective of the campaign and must be regarded to from a qualitative point of view only.

Figure 11 shows the time histories, during the first second of test, of the following signals: excitation of pilot valves[6]; position of the valves' stems; conductivity measured by probe C1. The valve stems start rising after more than 20 ms since the "opening signal", and further ~30 ms are necessary for the valves to fully open. During the next ~0.5 s the RD burst conditions are achieved, the injection is started and the "boron front" reaches the reference position (upper row first hole of the injection lance, probes C1/C2). The conductivity signal during its rising phase is very neat and allows quite a clear identification of the instant of the boron arrival (which was arbitrarily defined as the beginning of the concentration increase). After about 50 ms the conductivity has completed roughly 80% of its rise and starts showing rather wide oscillations, which can be explained by the highly turbulent flow near the probe tip.

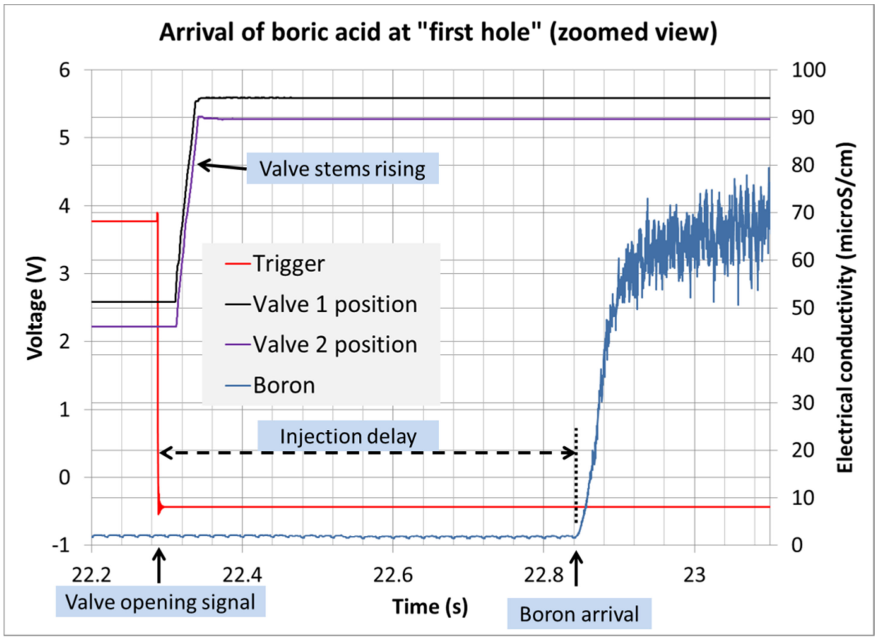

Figure 11. Results of a preliminary test (boron front arrival).

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[6] The "valve opening signal" corresponds to de-exciting the pilot valves coils.

Figure 12 shows the time histories of the gauge pressure measured at several key locations, for the entire duration of the injection (about 3.5 s for this particular test). The first half second since the valve opening signal is characterized by a rather severe pressure transient (waterhammer-like) affecting the injection line. The pressure downstream of the RD and at the lance inlet (CP004 and CP002 resp.) shows oscillations with a period of roughly 50 ms and a few tens of bars amplitude (rapidly damped after the RD opening). The pressure in the discharge tank, on the other hand, shows very tiny oscillations and a smooth increase during the injection. Toward the end of the injection, all the pressures stabilize at the same level, a few tens of bars above the initial pressure in the injection tank.

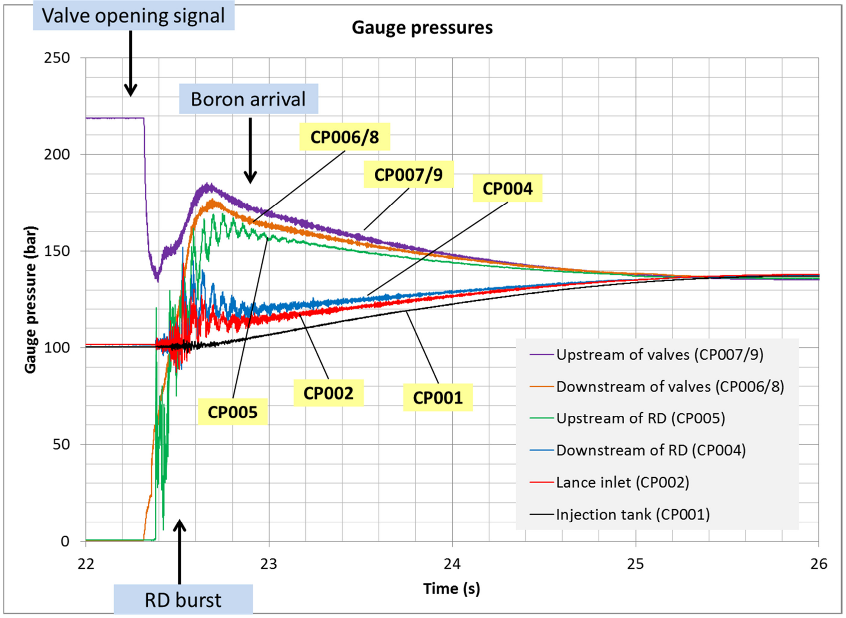

Figure 12. Results of a preliminary test (gauge pressures).

5. CONCLUSIONS

Assessing the capability of the Atucha-2 fast boron injection system to timely and safely shut the reactor power down in the case of a 2A-break LOCA with failed control rod insertion constituted one of the most important and challenging issues to be addressed in the NPP licensing process. This motivated NA-SA's decision to build a full-scale test facility that could provide a direct measurement of the injection time. The Boron Injection Test Facility was designed and constructed for such purpose in the framework of a cooperation agreement between NA-SA and the University of Pisa, the latter being in charge of providing technical and scientific support to all the phases of the project, and particularly of designing and supplying the instrumentation and data acquisition systems necessary for the measurement of the injection delay (as well as of the gauge pressure at several key locations).

The injection delay measurement is based on a conceptually quite simple idea, i.e. detecting the arrival of the borated water into the discharge tank by electrical conductivity needle probes. Six of such probes were realized by HZDR, with a customized design that could meet rather challenging specifications in terms of strength and measurement performance. In addition, eleven robust industrial transmitters capable of providing sufficiently fast and accurate gauge pressure measurements were used, and a compact, high-performance and user-friendly data acquisition system was setup to handle all those measurements.

The experimental campaign that NA-SA conducted on the BITF, consisting in several preliminary tests and about ten main tests (featuring different configuration), successfully met the objectives of assessing the JDJ system effectiveness and providing data useful to characterize the injection transient and to validate computer codes. The campaign was then complemented by an uncertainty analysis performed with the help of qualified computational models, so as to finally obtain an upper bound estimate of the injection time equal to **421 ms**, within **95/95** statistics.

6. ACRONYMS

ARN	Autoridad Regulatoria Nuclear
BEPU	Best Estimate Plus Uncertainty
BITF	Boron Injection Test Facility
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
DAS	Data Acquisition System
FSAR	Final Safety Analysis Report
GRNSPG	San Piero a Grado Nuclear Research Group
HZDR	Helmholtz Zentrum Dresden-Rossendorf
I&C	Instrumentation and Control
JDJ	Boron Injection System (German acronym)
KWU	Kraftwerk Union
LOCA	Loss Of Coolant Accident
NA-SA	Nucleoeléctrica Argentina Sociedad Anonima
NPP	Nuclear Power Plant
PHWR	Pressurized Heavy Water Reactor
RD	Rupture Device
RPV	Reactor Pressure Vessel
UNIPI	University of Pisa

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