Transient analysis of "2 inch Direct Vessel Injection line break" in SPES-2 facility by using TRACE code

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Abstract. In the past few decades a lot of theoretical and experimental researches have been done to understand the physical phenomena characterizing nuclear accidents. In particular, after the Three Miles Island accident, several reactors have been designed to handle successfully LOCA events. This paper presents a comparison between experimental and numerical results obtained for the “2 inch Direct Vessel Injection line break” in SPES-2. This facility is an integral test facility built in Piacenza at the SIET laboratories and simulating the primary circuit, the relevant parts of the secondary circuits and the passive safety systems typical of the AP600 nuclear power plant. The numerical analysis here presented was performed by using TRACE and CATHARE thermal-hydraulic codes with the purpose of evaluating their prediction capability. The main results show that the TRACE model well predicts the overall behaviour of the plant during the transient, in particular it is able to simulate the principal thermal-hydraulic phenomena related to all passive safety systems. The performance of the presented CATHARE noding has suggested some possible improvements of the model.

1. Introduction

After the Three Miles Island accident the International Community has changed the way to design nuclear power plants starting the growth of new advanced reactors which employ several safety systems that are able to mitigate a wide spectrum of accidents such as Loss of Coolant Accidents (LOCAs) or Station Black Out (SBO). Therefore, throughout last decades, lots of theoretical and experimental researches have been done to deeply understand the physical phenomena characterizing the innovative devices introduced in new nuclear designs and their performances during a postulated accident.

Westinghouse has designed and developed an advanced type of Pressurized Water Reactor (PWR) which is known in its two variants: the AP600 and its updated version AP1000. This kind of PWR employs a series of passive safety systems to mitigate the accidental transients. To achieve the design approval by U.S. NRC (United States Nuclear Regulatory Commission), from the early ’90, Westinghouse has strictly collaborated with some partners in an experimental programme which aim was to build several facilities simulating the thermal-hydraulic behaviour of AP600 reactor during different accident scenarios. One of these plants is SPES-2 which is an integral test facility built in Piacenza at SIET (Società Italiana per Esperienze Termofluidodinamiche) laboratories and simulating the primary circuit, the relevant parts of the secondary circuits and the passive safety systems typical
of the AP600 [1]. The aforementioned programme has demonstrated the effectiveness of the AP600 safety systems and the results obtained have been also used to provide data for system codes validation in the framework of International Code Assessment and Applications Program (ICAP). In fact code validation on qualified experimental data is a fundamental issue in the design and safety analyses of nuclear reactors.

This paper presents the numerical results that has been obtained by DEIM (Dipartimento di Energia, Ingegneria dell’Informazione e Modelli Matematici) of the University of Palermo and ENEA (Agenzia nazionale per le nuove tecnologie, l’energia e lo sviluppo economico sostenibile) for the “2 inch Direct Vessel Injection line break” with both TRACE and CATHARE best estimate thermal-hydraulic codes and their comparison with experimental data collected by SIET in the SPES-2 facility. The aim of this work is to study the differences on the code predictions considering the different modelling approach with one and/or three-dimensional components and to compare the capability of these codes. The main results show that the TRACE model well predicts the overall behaviour of the plant during the transient, in particular it is able to simulate the principal thermal-hydraulic phenomena related to all passive safety systems. The performance of the presented CATHARE model has suggested some possible improvements of the models.

2. SPES-2 facility description
The SPES-2 experimental plant, Fig. 1, is a full height and full pressure facility with an overall volume scale of 1/395 [2]. In addition, components and lines have been designed considering others scaling criteria to better duplicate the AP600 behaviour such as: conservation of thermodynamic conditions, preservation of fluid transit time, heat flux conservation in heat transfer components and conservation of elevation in lines and components.

![Figure 1. SPES-2 layout.](image)

2.1. Power channel
The power channel (PC) is composed of the following components: lower plenum, riser (including the core), downcomer (DC), upper plenum, upper head (UH) and downcomer-upper head by-pass (DC-UH by-pass). Ninety seven electrically heated rods are located inside the core, they reproduce the same geometry (rod pitch, diameter and length) as the AP600 rod bundle and the scaled full power used for the simulated transients is 4.99 MW. The downcomer is composed of an annular section in
which the four cold legs and two direct vessel injection (DVI) nozzles for safety injection enter and a tubular (TB) section that connects annular downcomer to the lower plenum.

2.2. Loop piping and pumps
The primary piping consists of two loops (loop A and B) each one including one hot leg (HL) and two cold legs (CLs). The hot leg reproduces the geometry of the AP600 up to surge line nozzle (same L/D in the horizontal section and same angle in the inclined section). The AP600 two cold legs per loop design is reproduced as well, however, they detach from a single coolant pump vertical discharge. The split from single pump discharge into the two cold legs is positioned at the elevation of the AP600 steam generator channel head in order to reproduce the geodetic flow path during a cold leg break transient: the broken cold leg must take the fluid from the unbroken one. The pumps (one per loop) are centrifugal, their suction line is horizontal while the delivery is directed downwards discharging in a pipe common to the two cold legs.

2.3. Pressurizer
The pressurizer (PRZ) consists of a cylindrical vessel with flanged ends and contains two immersion type electrical heaters each having a maximum controlled power of 16 kW. The pressurizer heat losses are compensated by means of six electrical external heaters. The pressurizer volume is scaled and the bottom elevation is preserved. The level swelling is preserved by ensuring that the average void fraction in the test is equal to AP600 for similar thermo-hydraulic conditions using Wilson bubble rise models [3].

2.4. Steam generators
The plant has two identical steam generators (SGs) that allow the transfer of thermal power from the primary to the secondary circuit. The steam generator primary side consists of a tube bundle and inlet/outlet plena. Its bundle includes 13 inconel 600 U-tubes assembled in a square array. The secondary side volumes are scaled by 1/395 and all vertical elevations are preserved up to the steam separator.

2.5. Passive safety systems
The passive safety systems are: two Core Make-Up Tanks (CMTs), an In-Containment Refueling Water Storage Tank (IRWST), a Passive Residual Heat Removal (PRHR) system, two Accumulators (ACCs), an Automatic Depressurization System (ADS) and all their connection lines to the primary system. The two CMTs are connected to the cold legs of loop B by two balance lines and they discharge cold water in the DVI lines through their injection lines. The volumetric scaling and the elevation change preservation have defined the component which is cylindrical with hemispherical heads. Their design has been developed so that the CMT metal mass is scaled to the AP600 CMT in order to preserve the rate of steam condensation on the walls. The IRWST provides low pressure gravity injection to each of the two DVI connections. The tank has been simulated conserving the water volume overall scaling, the water level and the bottom elevation. The IRWST also provides a heat sink for the PRHR. The PRHR consists in a full height C shaped heat exchanger with friction pressure drops maintained and the heat transfer area is scaled such that the natural circulation behaviour of the AP600 PRHR is simulated. The PRHR top is connected by a supply line with the hot leg A while its bottom is connected by a line to the pump suction A. The two accumulators in SPES-2 facility are not spherical as in AP600 design but they have been scaled preserving the volume of the accumulators in the reference plant. The gas (air) to water volume ratio is preserved. Each of their injection lines are connected to the respective DVI. The four stages of ADS consist of ball valves (one per stage) with an orifice in series to achieve the proper scaled flow area. The two sets of piping connected to the steam space of the pressurizer in the AP600 are combined into single set with the first, second and third stage valves in SPES-2. The ADS fourth stage is located on the hot legs of the primary piping.
3. TRACE and CATHARE codes brief description
Best-estimate thermal-hydraulic system codes are complex tools developed to simulate both normal and transient conditions in nuclear power plants. The general objective of the best estimate approach is to get an evaluation of the plant behaviour which will be as realistic as possible.

3.1. TRACE code
The TRACE code is an advanced best-estimate code, two-fluid, thermal-hydraulic computer code designed for use in realistic studies of light water reactors. The capability exists to model thermal-hydraulic phenomena in both one and three dimensional space. In addition, it contains not only a point kinetics model but also the capability to be coupled with external 3D neutronic codes-and the possibility to be managed through the graphical user interface SNAP [4], [5].

3.2. CATHARE code
The Code for Analysis of THermalhydraulics during an Accident of Reactor and safety Evaluation (CATHARE) is a system code for PWR safety analysis, accident management, definition of plant operating procedures and for research and development. The CATHARE code is based on a 2-fluid 6-equation model including non-condensable gas equations and additional equations for radio-chemical components transport. The code would be utilized by means of the graphical user interface GUITHARE [6], [7].

4. TRACE model
The SPES-2 TRACE nodalization, Fig. 2, has been made by using TRACE V5.0 patch 3 and it models in detail the experimental facility [8], [9].

The total number of thermal-hydraulic components presented in TRACE model is 432, being 83 PIPEs, 13 VESSELS, 26 VALVEs, 11 BREAKs, 2 FILLs, 4 SINGLE JUNCTIONs, 11 TEEs, 2 PUMPs, 276 HEAT STRUCTUREs and 4 POWERs. In addition 42 TRIPs, 124 CONTROL BLOCKs, 505 SIGNAL VARIABLEs and 144 TABLEs complete the model. In particular, where the 1D approach is not sufficient (i.e. secondary flows are not negligible) as in the power channel, in the steam generators and in the IRWST pool, the 3D component “VESSEL” has been used.

4.1. Principal physical models adopted
In order to better simulate the behavior of the various systems during a SBLOCA, several physical models made available by the code have been used [10].
The “level tracking” model have been adopted in all vertical components to localize, as well as possible, the liquid-gas interfaces. Models of counter-current flow limitation (CCFL) have been used at the cell junctions where this event was expected during flooding and reflux condensation phases. The “offtake” model has been applied at the side junctions of ducts where a horizontal stratified two-phase flow was expected to predict the correct offtake flow quality that would have come out from the main tube; this has allowed to better simulate the void fraction distribution downstream of the junctions that connect the primary circuit to some passive safety systems which mass flow rates are deeply influenced by the buoyancy force. At cell edges that simulate the break and the ADS orifices the “critical flow” model has been used.

4.2. Power channel, steam generators and IRWST
The lower plenum, the riser and the upper head have been described using the VESSEL component: its nodalization consists of 38 axial levels, 4 radial rings and 8 azimuthal sectors. The annular downcomer has been simulated apart by means a VESSEL component with 12 axial levels, 2 radial rings and 10 azimuthal sections to better simulate the circumferential position of the nozzles and fillers with the purpose of reproducing as best as possible the azimuthal pressure drops. Fig. 3 shows the noding of power channel. Four PIPE components have been used to describe the tubular downcomer and upper head-downcomer by-pass.
The upper part of each steam generator has been described using three VESSEL components which have been needed to better reproduce the geometrical features and the complex flow paths taking place inside steam separator and steam dome.

The IRWST pool nodalization has been made through the application of a cartesian VESSEL that is divided in 24 axial levels, 3 X-sections and 6 Y-sectors.

**Figure 2.** SPES-2 TRACE-SNAP nodalization. **Figure 3.** Power channel cross sections.

### 5. CATHARE model

The latest version V2.5_2 of CATHARE 2 has been adopted to simulate the SPES-2 facility, the related nodalization has been developed by respecting the geometrical dimensions of different parts and components as well as the topology of the circuits. In particular, the modular structure of the code has allowed to find a good compromise to preserve heights, flow areas and fluid volumes. It is worth to remind that the facility is scaled 1/1 in height and 1/395 in volume respect to the AP600 reactor. The annular downcomer has been simulated by means a VOLUME. In Figs. 4 and 5 are reported the CATHARE nodalization schemes of the primary vessel and of the loop A that includes the pressurizer.

**Figure 4.** CATHARE PC nodalization. **Figure 5.** CATHARE loop A nodalization
6. Small break LOCA phenomenology in AP600

The AP600 Small Break LOCA (SBLOCA) transient can be subdivided into four different phases that characterize thermal-hydraulic phenomena, namely the blow-down phase, the natural circulation phase, the ADS blow-down phase and the IRWST injection phase [11]. Fig. 6 shows the pressure transient for a typical SBLOCA event. Superimposed on the graph is the relative timing of events as described in the following sections.

6.1. Blow-down phase

During this phase the primary system pressure decreases from the operating pressure to the secondary-side pressure of steam generator, then reaches stable primary pressure. After the break is opened the coolant mass is lost from the primary system and the pressure falls continuously as consequence. When the pressurizer pressure reaches the setpoint value of 12.41 MPa, the reactor scram and steam generator main steam line isolation valves (MSLIVs) closure are actuated. Quickly the pressure falls below 11.72 MPa: “safety signal” condition is reached. This signal causes the opening of the CMT and PRHR isolation valves (CMTIVs, PRHRIVs) and, after a short delay, the reactor coolant pumps coastdown. Meanwhile the core power decrease according to decay heat model and the reactor system starts to be cooled by natural circulation that occurring in CMT and PRHR lines; moreover the energy is removed from reactor system by heat up of steam generators and fluid loss through the break. At the end of the blow-down phase the pressurizer is empty of water but full of steam. The liquid in the upper plenum and upper head may flash and the upper head may begin to drain.

The phenomena that take place in this phase are common to all PWR reactors except that behaviour of CMTs and PRHR that are installed only in AP600 nuclear power plant.

6.2. Natural circulation phase

This phase covers the period between the stabilization of the primary pressure with the secondary-side pressure and the ADS stage 1 opening. The primary system is cooled down by various modes of natural circulation that depend on the system inventory; that is, single-phase natural circulation, two-phase natural circulation and reflux condensation.

The decay heat is removed through the break, steam generators, PRHR and CMTs recirculation flow. The steam generator U-tubes drain relatively quickly and, as consequence, the IRWST becomes the main heat sink for the reactor coolant system. During the time between the steam generators isolation and ADS activation, the PRHR and the break flow provide a large heat removal rate. The IRWST is heated up by the two-phase mixture which flows into PRHR tubes. The heat transfer in the pool occurs...
either by free convection or boiling depending on the tube outer wall temperature and tank water temperature near the tubes. The CMTs continue the recirculation mode, providing heat removal and a small net injection to the primary system until the cold legs and balance lines drain; when this occurs the steam can flow up to the CMT top, after which CMT injection grows and its level drops continuously. When CMT level falls below ADS actuation setpoint the third phase of the SBLOCA transient begins.

6.3. ADS blow-down phase
At the beginning of the ADS blow-down phase, the primary system is depressurized through the ADS stage 1 valve opening. After ADS stage 1 valve opening, to ensure a controlled depressurization of primary system, the other two stages are opened via progressive delay within few minutes. When either CMTs water level falls below 20% of the nominal, the fourth-stage valves attached to both hot legs open and discharge water directly to the containment.
Since ADS stage 1 actuation results in a reduction in pressure at the top of the pressurizer, the pressurizer two-phase fluid level increases markedly. Thus, pressurizer level and surge line phenomena are important factors in the depressurization behaviour following stages actuation. Fluid flashing occurs again in the reactor coolant system due to increased depressurization rate after the ADS is actuated.
The accumulators start to inject cold water once the pressure drops below 4.83 MPa. This reduces the discharge flow from the CMTs, which may be stopped temporarily due to increased backpressure in the DVI lines, caused by the high accumulator flow rate. ADS stage 4 performance is affected by the nature of flow in the hot legs and by drainage from the pressurizer.
The flow through the ADS valves is the major factor that determine the instant when the primary system pressure drops such as allowing the gravity injection of water from IRWST.

6.4. IRWST injection phase
When this phase starts the pressure of the primary circuit is near the containment pressure. The injection from the IRWST signs the end of the SBLOCA transient and the beginning of the long-term cooling.
During IRWST injection phase, the core coverage with liquid or two-phase mixture depends upon the decay heat level and the IRWST injection flow. At this time the CMT flow can be stopped again owing to the increased IRWST gravity drain rate, anyway the phenomena that affect the CMT behaviour are less important compared to those of IRWST.

7. Two inch Direct Vessel Injection line break in SPES-2
The aim of the test was to investigate the response of the passive safety systems during the whole transient. The test is characterized by a single failure event: one of the two ADS stage 4 valves had to remain closed.

7.1. Experimental test description
The test starts at time 0 s by opening the break valve from full power steady-state condition. The pressurizer pressure and water level quickly decrease owing to the mass lost from the break. About 62 seconds after the beginning of the transient the pressure reaches the “R-signal” (12.41 MPa) so the reactor scram is actuated, 2 seconds later the main steam isolation valves are closed. The “S-signal” setpoint (11.72 MPa) is crossed at 70 s, 2 seconds delay the CMTs and the PRHR isolation valves are opened, at the same time the main feedwater isolation valves (MFWIVs) close. The primary pumps starts coastdown 16.2 second after S-signal. Meanwhile the primary pressure falls to the secondary-side pressure of steam generator and it reaches a quasi-stable condition. Soon after S-signal actuation the CMTs start injection in recirculation mode; when the steam occurs in cold legs, at about 400 s, it can flow through the balance line reaching the CMTs which begin to drain. Moreover after presence of steam into the top of the CMTs the primary pressure restarts to drop slowly owing to expansion of
steam in large volumes. The CMT flow rates, as expected, are slightly asymmetric during both recirculation and drain down phases.

ADS stage 1 opens at 809 s, 30 second after CMT A level reaches 67% of nominal value. ADS stage 2 and 3 open with a delay of 95 and 215 seconds, respectively, from the actuation of the first stage. At this time primary system depressurization becomes more rapid, increasing the presence of steam in the system.

Accumulator injection begins contemporaneously ADS stage 1 opening, once the pressure drops below about 4.87 MPa and the flow rate released reaches its maximum value after the ADS stage 3 actuation. The pressurizer level rises after ADS stage 1 opening and it continues to increase until accumulators injection stops.

At about 30 minutes since the beginning of the transient, CMT A level falls under 20% of its nominal value and, 60 s after, the ADS stage 4 opens. Since ADS stage 4 actuation the pressurizer goes back to emptying again.

IRWST injection begins about 100 seconds later: this signs the end of the SBLOCA transient and the beginning of the long-term cooling phase.

7.2. Comparison between experimental data and numerical results

The SPES-2 transient analysis here presented has been performed by the research groups of DEIM of the University of Palermo and ENEA of Bologna. In order to improve the prediction capability of the SPES-2 TRACE and CATHARE models, several nodalizations of the experimental plant have been studied and they have been used to perform different simulations of steady-state conditions comparing the results with data available in literature [12], [13]. A great importance was given to the correct simulation of the heat losses that affected the behaviour of these kinds of facilities especially during the analysed transient and to the simulation of the pressure distribution and pressure drops along all circuits.

In the following all figures will show the values normalized: Y-axes are normalized over the maximum value of plot scales, while X-axes are divided by a constant value.

The simulation of the transient by using TRACE code has been performed until the beginning of the long-term cooling phase, since the main phenomena were investigated. The TRACE numerical results show a good agreement with experimental data. The calculated primary pressure well reproduces the facility behaviour during the main phases of the transient though some mismatch is present in timing and value when a slow depressurization occurs after the beginning of the CMTs drain down phase, Fig. 7(a). The CMT A flow rate predicted by TRACE code is quite similar to experimental data in trend and values, Fig 8(a), as well as the calculated PRHR flow rate until the onset of ADS blow-down phase when numerical results show an unstable flow rate which did not appear in the experimental test, Fig. 9(a). These oscillations are a result of the calculated ADS flow rate which has more fluctuations than the experimental one although its mean value is very similar to experimental data. Anyway the overall behaviour of plant is well predicted by TRACE code providing a confirmation of the model capability to simulate the thermal hydraulic phenomena that occur in passive systems during the transient.

The main results obtained by a preliminary CATHARE calculation are compared with the experimental trends in Figs. 7(b) to 9(b). The Fig. 7(b) shows the fast depressurization of the primary system, this behaviour is well predicted by CATHARE in the first seconds of the transient while in the following the experimental depressurization results faster than in the simulation. The Figs. 8(b) and 9(b) report respectively the flow rate discharged by the CMT A in the primary side of the plant and the mass flowing in the PRHR after the break opening. As can be seen, the flow rates predicted by CATHARE are not in good agreement with the experimental data. This could be a consequence of the CATHARE nodalization: the annular downcomer representation by means of a volume (0D) module of CATHARE is not able to describe the real behaviour of this part of plant. In fact considering the complex phenomena that occur into this component the noding should be updated considering the possibility to introduce a 3D element to describe the behaviour of the annular downcomer.
Figure 7(a). TRACE vs EXP primary pressure.

Figure 7(b). CATHARE vs EXP primary pressure.

Figure 8(a). TRACE vs EXP CMT A flow rate.

Figure 8(b). CATHARE vs EXP CMT A flow rate.

Figure 9(a). TRACE vs EXP PRHR flow rate.

Figure 9(b). CATHARE vs EXP PRHR flow rate.
8. Conclusions
The present work concerns a comparison between experimental and numerical results obtained for the “2 inch Direct Vessel Injection line break” in SPES-2. This facility is an integral test facility built in Piacenza at the SIET laboratories and simulating the primary circuit, the relevant parts of the secondary circuits and the passive safety systems typical of the AP600 nuclear power plant. The numerical analysis here presented was performed by using TRACE and CATHARE thermal-hydraulic codes with the purpose of evaluating their prediction capability. The main results show that the TRACE model well predict the overall behaviour of the plant during the transient and it is able to simulate the principal thermal-hydraulic phenomena related to all passive safety systems; in particular, physical models such as CCFL and “offtake” manage to respectively catch the upper-plenum/upper-head pool formations and the two-phase flows that move toward CMTs and PRHR. The performance of the presented CATHARE model has suggested a possible improvement of the geometrical nodalization to predict the behaviour of the facility during the transient that is the application of 3D module (instead of 0D module) with the aim of describing as well as possible multidimensional effects in the annular downcomer which is a key component for steam displacement around the primary circuit during the two-phase natural circulation.

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