Analysis of a Station Black-Out transient in SMR by using the TRACE and RELAP5 code

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Abstract. The present paper deals with the investigation of the evolution and consequences of a Station Black-Out (SBO) initiating event transient in the SPES3 facility [1]. This facility is an integral simulator of a small modular reactor being built at the SIET laboratories, in the framework of the R&D program on nuclear fission funded by the Italian Ministry of Economic Development and led by ENEA. The SBO transient will be simulated by using the RELAP5 and TRACE nodalizations of the SPES3 facility. Moreover, the analysis will contribute 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 to describe the SPES3 facility behaviour.

1. Introduction
In the last few years, several new advanced integral Small Modular Reactor (SMR) designs have been considered by the International Community. The integral nature of these reactors requires the analyses and the characterization of the phenomena characteristic of these designs such as, the primary to secondary heat transfer in integrated Steam Generator (SG), the natural circulation in passive systems and Reactor Pressure Vessel (RPV)/containment coupling both in Design and Beyond Design Basis Accidents conditions (DBA and BDBA). The SPES3 facility, being built at the SIET laboratories in the framework of the R&D program on nuclear fission funded by the Italian Ministry of Economic Development and led by ENEA, is a simulator of an integral type SMR simulation. This facility can be used to create a database for the characterization of the SMR phenomenology and to validate and assess best estimate thermal hydraulic system codes, a keypoint in the design and safety analyses of Nuclear Power Plants (NPP). Complete nodalizations of SPES3 were developed for TRACE and RELAP5 codes in order to investigate the code responses by the simulation of the same accidental transients. As a consequence of the accident occurred at Fukushima Daiichi NPP in Japan, the guarantee of reliable safety functions against any initiating event, e.g. earthquake and flooding, has become fundamental to evaluate the consequences of loss of electrical power, including the complete SBO. The SBO scenario involves a loss of offsite power, failure of the redundant emergency diesel
generators, failure of alternate current (AC) power restoration and the eventual degradation of the Reactor Coolant Pump (RCP) seals resulting in a long-term loss of coolant.

The objective of the present paper is to investigate the evolution and the consequences of a transient due to a SBO initiating event in the SPES3 facility. Moreover, the analysis will contribute 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 to describe the SPES3 facility behaviour.

2. The SPES-3 Facility

The scheme of the SPES3 facility is shown in Fig. 1. SPES3 is an integral test facility, based on the IRIS reactor design [2], reproducing the primary, secondary, containment and safety systems. It allows to test the plant response to postulated accidents and to investigate general interest thermal-hydraulic phenomena like primary to containment dynamic coupling.

![Figure 1. SPES3 facility scheme.](image)

The reactor vessel includes the internals, consisting of the electrically heated core simulator, the riser with Control Rod drive Mechanisms (CRDM), the Pressurizer (PRZ), the pump suction plenum, the helical coil SG, the downcomer (DC) and the lower plenum. Two Emergency Boration Tanks (EBT) are simulated and connected to the Direct Vessel Injection lines (DVI), devoted to direct injection of emergency fluid into the vessel. Each secondary loop is simulated up to the main isolation valves and includes the feed line, the SG, the Steam Line (SL), and the Emergency Heat Removal System (EHRS) with a vertical tube heat exchanger immersed in a Refuelling Water Storage Tank (RWST).

The containment compartments are simulated by tanks, connected to each other by pipes and to the RPV by break lines. They include Dry-Well (DW) and Reactor Cavity (RC), representing the dry zone surrounding the RPV, respectively above and below the mid-deck plane; Pressure Suppression Systems (PSS) representing the wet zone around the lower part of the RPV, suitable to dump pressure in case of containment pressurization; Long-term Gravity Make-up Systems (LGMS) representing the cold water reservoir to be poured into the RPV when depressurized.

The two stages of the Automatic Depressurization System (ADS) are simulated, connected to the PRZ top, with stage I discharging into the Quench Tank (QT) and stage II directly connecting RPV and DW at high plant elevation.

The facility allows to test both LOCAs and secondary side breaks (DBA and BDBA) as well as to perform separate effect tests on particular components such as SG-EHRS thermally coupled to RWST. The passive EHRS consists of four independent subsystems. Each subsystem has an heat exchanger connected to a separate SG feed steam line and immersed in the RWST, located outside the containment structure.
The RWST water provides the heat sink for the EHRS heat exchangers operating in natural circulation. The secondary fluid in transient conditions comes from the SG outlet and arrives, for natural circulation, in the heat exchanger where it is condensed by transferring energy to the RWST water, then it returns back to the SG.

3. TRACE nodalization

A TRACE model of the SPES3 facility has been developed for design support, pre-test calculations and when the facility will be built, for post-test calculations. The SPES3 TRACE nodalization models the primary and the secondary system, the containment structures and the safety systems simulated in the SPES3 facility. The RPV nodalization models the lower DC, the Lower Plenum (LP), the core, the core bypass, the riser, the PRZ, the pump suction plenum, the outlet pump and connecting piping, the SG primary side and the riser to DC check valves. The three helical coil SGs are modelled with three different equivalent groups of pipes thermally coupled with three different SG primary side regions. The secondary system-A (B, C) consists of the FL-A (B, C), the SG-A (B, C) tubes and the SL-A (B, C). The SG-A (B) consists of a single group of pipes equivalent to the 14 helical coils. The SG-C consists of two single group of pipes each equivalent to 14 helical coils. The SPES3 TRACE nodalization models the three different EHRS loops A, B and C and the related RWST. The RWSTs are modelled with the 3D component “vessel”; Fig. 2 shows primary and secondary systems. The heat exchanger-A (B) is immersed in the RWST-A/B. The CL-A (B) exits from the heat exchanger-A (B) bottom and connects to the FL-A (B). In particular, the EHRS-A (B) consists of the HL-A (B), the heat exchanger-A (B) and the CL-A (B). The HL-A (B) detaches from the SL-A (B) and enters the heat exchanger-A (B) top.

![Figure 2. SPES3 TRACE nodalization.](image)

4. RELAP5 noding

The SPES3 facility nodalization [4] contains: the Primary System, the Secondary Systems, the Emergency Heat Removal System and the Containment System. The Primary System RELAP5 noding includes the following main regions: Lower downcomer, Lower plenum Core, Core by-pass, Lower riser, RCCA zone, Upper riser, CRDM zone, Pressurizer Pump Suction plenum, Outer Pump and connecting piping. Primary side of SG-A, -B and -C. Riser-SG primary side connection check valves. Particular attention was focused on the EHRS-RWST modeling (see the Fig.3). The choice to model the RWST with two slices connected by transversal junctions is based on lessons learned by an
experimental campaign at SIET and post-test calculations of an similar in-pool immersed heat exchanger [5].

![Figure 3. SPES3 facility scheme.](image-url)

The EHRS-C consists of the HL-C, the heat exchanger-C and the CL-C. The heat exchanger-C is immersed in the RWST-C. The different SPES3 containment compartments and the connecting pipes are modelled. The two EBT tanks are modelled separately and each one is connected to the related DVI line. In particular, the DW, the RC and the PSS are modelled with the 3D “vessel” component. The SPES3 ADS lines are modelled separately [8], [9].

5. **SPES3 SBO Transient**

The main phases of the transient can be summarised in:

1. The loss of off-site power is assumed to be contemporary to the earthquake and to trigger the RCP and MFW pump coast-down. Natural circulation establishes through the pump-bypass and RI (Riser) – DC (Downcomer) check valves;

2. the low FW signal triggers the reactor scram;

3. the start-up FW signal (postulated for SMRs and not simulated in SPES3) is assumed to fail and this gives permission to isolate the SGs and trigger the EHRS-A and B;
4. the low collapsed level signal in the SG, secondary side, triggers the SG isolation and actuates the EHRS-A and B; RPV level decreases for system cool-down. Pump by-passes uncover and natural circulation occurs only through the RI-DC check valves. The RPV depressurizes;

5. the low core inlet coolant temperature signal actuates the EBTs that inject water until RPV and EBT level equalize;

6. in the long term, the plant continues to be cooled by the EHRSs that removes the core decay heat to the RWSTs.

6. SBO Simulation

The RELAP5 and TRACE simulations have been carried out for 150000 s but the pictures show data for the first 50000 s because this period of time is sufficient to investigate the principal phenomena and differences between the two calculations. The steady-state conditions starting point for the transient are summarized in Tab.1.

| SPES3                  | Unit | RELAP5 | TRACE |
|------------------------|------|--------|-------|
| Pressurizer pressure   | MPa  | 15.509 | 15.512|
| Core power             | MW   | 6.5    | 6.5   |
| Core inlet fluid temp. | K    | 563.72 | 564.52|
| Core outlet fluid temp.| K    | 601.64 | 602.54|
| Core mass flow         | kg/s | 29.56  | 29.32 |
| SG outlet pressure     | MPa  | 6.01   | 6.11  |
| SG feed water temp.    | K    | 496.95 | 496.92|
| SG-A steam out. temp.  | K    | 548.90 | 550.00|
| SG-B steam out. temp.  | K    | 548.90 | 550.00|
| SG-C1 steam out. temp. | K    | 549.09 | 550.20|
| SG-C2 steam out. temp. | K    | 549.09 | 550.21|
| SG-A mass flow         | kg/s | 0.81   | 0.81  |
| SG-B mass flow         | kg/s | 0.81   | 0.81  |
| SG-C1 mass flow        | kg/s | 0.81   | 0.81  |
| SG-C2 mass flow        | kg/s | 0.81   | 0.81  |
| RWST fluid temp.       | K    | 293.51 | 293.45|

The list of the main events occurring during the transient with timing is reported in Tab. 2 and the main quantities, evidencing the details of the above described phases, are compared in Fig. 6 to Fig. 14. The earthquake occurs at time 0 and the loss of off-site electric power is contemporary. The pumps of the system are switched-off and the coast-down starts for the RCP and the FW pumps. The reactor scram occurs at 1.24 s, on Low FW signal, set at 75% of nominal feed-water mass flow. The Start-up feed-water, which should intervene at the reactor scram, is assumed to fail and this gives permission for secondary loop isolation.
| Phases and events [s]                           | RELAP5 | TRACE |
|------------------------------------------------|--------|-------|
| Earthquake and Loss of off-site power         | 0      | 0     |
| RCP coast-down starts                         | 0      | 0     |
| MFW pump coast-down starts                    | 0      | 0     |
| Low FW signal                                 | 1.24   | 1.24  |
| SCRAM Signal and Start-up FW actuation fails  | 1.24   | 1.24  |
| Natural circulation begins (RI-DC)            | 20     | 6     |
| Circulation begins pump by-pass               | 20, 22 | 5     |
| Low SGs level signal                          | 43     | 54    |
| MFIIV-A,B,C closure start                     | 43     | 54    |
| MSIV-A-B-C closure start                      | 43     | 54    |
| EHRS-A and B opening start                    | 43     | 54    |
| EHRS-A peak mass flow                         | 44     | 60    |
| EHRS-B peak mass flow                         | 44     | 60    |
| RWST-A/B begins to heat-up                    | 90     | 55    |
| Secondary loop-A pressure peak                | 143    | 128   |
| Secondary loop-B pressure peak                | 143    | 129   |
| EHRS-A power peak                             | 200    | 411   |
| EHRS-B power peak                             | 200    | 502   |
| Low PRZ pressure                              | 1160   | 748   |
| Low core inlet coolant temperature            | 2960   | 3601  |
| EBT-A and B valve opening start               | 2960   | 3601  |
| Natural circulation interrupted at SGs top    | 3680   | 8900  |
| EBT injection to RPV stop                     | 5310   | 4344,4908 |
| Core in saturation conditions                 | 37200  | 16689 |

The pump head decrease lets the RI-DC and the pump by-pass check valves open and allows natural circulation between riser and SG annuli at lower and high elevation in the RPV. In the secondary side the MFW pump is assumed to stop in 4.9 s. The loss of main feedwater causes the reduction of mass inventory in the SGs, secondary side. The SG low level signal occurs when the collapsed level reaches 0.25 m (see Fig. 4). This signal starts the secondary loop isolation and actuates the EHRS-A and B. Natural circulation starts in SG-A and B, thanks to EHRS-A and B intervention, while SG-C is supposed to fail. For about an hour the SG mass flowrates calculated by the RELAP5 simulation are 13% higher than that obtained from the TRACE simulation, consequently, the power removed by the EHRSs in RELAP5 is 30% greater than in TRACE, Fig. 5, Fig. 6. This is the main reason why within the primary, Fig. 7, and secondary circuits the mass flow rate calculated by RELAP5 is greater than that predicted from the TRACE. Due to the RPV level decrease for system cooling, the pressurizer is empty before the transient reaches the 30 minutes, Fig. 8. Power is rejected to the RWST-A/B that begins to heat-up in one minute and reaches saturation at about 2 hours and 25 minutes, Fig. 9; the RWST A/B mass decreases for water evaporation.
The primary side pressure decreases for the system cool-down, Fig. 10. The inlet and outlet core temperatures together with the saturation temperature corresponding to core outlet pressure are shown in Fig. 11 for RELAP5 transient and in Fig. 12 for TRACE transient. It is possible to observe that in RELAP5 the fluid temperatures in the core are always lower than in TRACE. For this reason the set-point of 533.15 K for the low core inlet coolant temperature is reached at about 50 minutes in RELAP5 and 10 minutes later in TRACE analysis. The signal triggers the EBT actuation by opening the EBT valves in 15 s. Cold water is injected into the RPV, through the DVI lines, and hot water and steam replace the EBT water through the EBT top line, connected to the RPV. The RPV mass inventory slightly increases thanks to the EBT injection and then it remains stable, Fig. 13.
In RELAP5, at about 37000 s, the core outlet temperature is in saturation condition, anyway the core is always under single-phase water, whereas in TRACE the core outlet temperature is in saturation at about 16700 s and at the top of active fuel begins to boil, Tab. 2. However, in both cases no temperature excursion occurs on the heated rods cladding, Fig. 14. After 12 hours, the core decay power is about 1% than nominal value and is reached the long term condition: the EHRS-A and B remove the core decay power and slowly cool-down the system, the mass flow rate is stable around 2 kg/s and the pressure at about 0.3 MPa. The reason for the differences between TRACE and RELAP5 analysis is due to the different models (e.g. RWST noding) and approaches used in the development of the nodalizations for the two codes.
Figure 10. Primary pressure.

Figure 11. Core inlet, outlet and saturation temperature in RELAP5.

Figure 12. Core inlet, outlet and saturation temperature in TRACE.

Figure 13. RPV mass inventory.
Conclusions

The simulation of the SBO allowed to understand the phenomena occurring in the transient and to verify that the plant is suitable to cope with this kind of accident. No particular or critical situation occurred and the system slowly cools-down. Anyway, notwithstanding the difference in the codes and modeling, results are comfortably similar in trend and values, providing a further confirmation of the SPES3 facility design choices. In the future, the simulation with the two codes of other cases, included in the test matrix, will provide further information for a deeper investigation of the phenomena and the possible optimization of the system.

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