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CONTENTS

LIST OF ABBREVIATIONS AND SYMBOLS

APROS	Finnish computer code
ATHLET	German computer code
BRU-A	steam dump valve to the atmosphere
ECCS	emergency core cooling system
EOP	emergency operating procedure
F&B	feed and bleed
HA	(hydro) accumulator
HPIS	high-pressure injection system
LOCA	loss-of-coolant accident
LOOP	loss of off-site power
LPIS	low-pressure injection system
MCP	main circulating pump
MPa	megapascal (1 MPa = 10 bar)
NPP	nuclear power plant
PACTEL	Finnish test facility
PCT	peak cladding temperature
PMK	Hungarian test facility
PORV	power-operated relief valve
RCP	reactor coolant pump (= MCP)
RELAP5	American computer code
RPV	reactor pressure vessel
SBLOCA	small-break loss of coolant accident
SG	steam generator
T_{clad}	fuel cladding temperature
VVER	Russian-type PWR
WP	work package

EXECUTIVE SUMMARY

The IMPAM-VVER project dealt with the following safety issue identified in recent VVER safety studies: Is it always possible to depressurise a VVER nuclear power plant (NPP) efficiently enough down to the operating pressure of the low-pressure safety injection (LPSI) system and thus ensure sufficient core cooling at all times? The main practical objective was to investigate which means and criteria for starting appropriate depressurisation measures, like the accumulators and primary/secondary feed and bleed, would be most efficient. It also assessed whether the computer codes can adequately predict the important relevant phenomena.

The research activities were divided in the following two work packages (WPs):

(1) Experimental investigation using PMK-2 and PACTEL test facilities, and
(2) Pre- and post-test analyses of the experiments, and analyses of relevant NPPs using advanced codes.

Three types of experiments were carried out:

(1) Investigation of post-LOCA (loss-of-coolant accident) cool-down procedure,
(2) Investigation of the starting conditions for primary feed and bleed after LOCA, and
(3) Other studies, like investigation of the effect of reverse steam generator heat transfer.

The emphasis was on experiments to investigate whether the issues raised should require consideration of changes in operating practices. Advanced computer codes were used for defining and analysing the experiments, as well as for analysing corresponding transients in real VVER NPPs, thus providing valuable assessment for the codes in predicting the associated complex phenomena. The European thermo-hydraulic system codes CATHARE, ATHLET, APROS were used, as well as the American RELAP5 code. The project utilised two unique integral thermo-hydraulic VVER-440 facilities (the only ones in the world), which offered an invaluable possibility to address the essential scaling effects by testing their counterpart. The instrumentation of the facilities was upgraded by special advanced equipment from FZR, Germany. Industrial participation by VVER utilities ensured focus on the production of practically useful results.

The experiments and analyses confirmed the beneficial effect of reduced accumulator pressures in pressure reduction and ensuring core cooling, and indicated that the time window between secondary and primary bleeds foreseen in the current EOPs may be too short. When the HPSI is unavailable, the secondary bleed should be started as soon as possible. Although the NPP analyses showed generally rather good agreement with the experiments, the scaling factor and the test facility design (e.g. number of loops) had some significant effects on the results. The computer code assessment also proved important, and indicated that further work is still needed to address some phenomena, like pressuriser-spray effectiveness, pressuriser behaviour during refill, and swell-level behaviour at low pressures.

The project results will effectively contribute to improved VVER safety by providing publicly available information for both utilities and safety authorities. However, it is recommended that more investigations be carried out by the utilities to further ensure that the primary system can be effectively depressurised in all potential VVER NPP accident and transient situations, and that sufficient cooling of the reactor core can be provided at all times.

The extended version of this final report [1] provides a more detailed description of the project and its results.

1. OBJECTIVES AND SCOPE

There is strong European and even global interest to further ensure that VVER reactors are operated safely everywhere, and a need for publicly available practical safety research results utilisable in all VVER countries. The objective of this project was to resolve a safety issue identified in recent safety studies. The project utilised the only integral VVER-440 test facilities in the world, PACTEL and PMK. The participation of VVER utilities ensured the practical value of the project. The results can be used in all VVER countries since they are public, and will effectively contribute to improved VVER safety.

In some VVER small-break LOCA (loss-of-coolant accident) scenarios, potential problems to depressurise the primary system effectively to allow the emergency core coolant injection from the low-pressure system had been identified. The main objective of this project was to investigate which means and criteria for the depressurisation measures, like feed and bleed, would be most efficient. Two unique test facilities of different size and several different advanced computer codes were utilised. A secondary objective was to assess whether these computer codes can adequately predict the associated complex phenomena, and to adequately analyse relevant transients in real VVER nuclear power plants.

The research was complementary to the PHARE programme, which has traditionally focused on practical implementation of accident management measures and provision of related equipment to the power plants. To cover practical aspects of the implementation of AM measures and to support licensing decision-making, a related regional TSO PHARE project was initiated by Hungary.

The present project makes use of the modern measurement system of the PMK-2 facility that was upgraded in the recently finished PHARE project SRR3. In addition, void probes and pressure transducers purchased in the framework of the EC project WAHA-LOADS were used, as well as the new advanced probes provided by FZ Rossendorf for this project. The project had good connections with the EC project VERSAFE (Concerted Utility Review of VVER-440 Safety Research Needs – part of the PLEM cluster) through its partners Fortum Nuclear Services, the co-ordinator of VERSAFE, and through Paks NPP, an important partner in VERSAFE.

2. WORK PROGRAMME

2.1. Experimental investigation using PMK-2 and PACTEL test facilities

The following types of experiments were carried out:

(1) Investigation of post-LOCA cool-down procedure
(2) Investigation of starting conditions for the primary feed and bleed during LOCA
(3) Investigation of effect of reverse steam generator heat transfer for feed and bleed
(4) Investigation of 30 % break during the cool-down state of the plant (added later).

Six experiments (including one additional) were performed using PMK and three using PACTEL. One PMK test addressed test type 1, three PMK and two PACTEL tests type 2:

- a "base case" by both facilities, with bleed actions following the plant procedures;
- a PMK test with secondary and primary bleed started as early as possible;
- a "base case" by both facilities, with reduced accumulator pressure (counterpart test).

One test (of type 3) was finally decided to be executed by both facilities as another counterpart test (the PMK test was additional and voluntary to the original project plan). PMK would perform one test of type 4. The instrumentations of both facilities were upgraded by special advanced equipment from FZR.

2.2. Analyses of PMK and PACTEL experiments and relevant NPP scenarios

Advanced computer codes were used for both defining and analysing the experiments, and to assess their capabilities in predicting the associated complex VVER-related phenomena. Important European thermo-hydraulic system codes, e.g. CATHARE, ATHLET, and APROS, were used.

In order to further address the scaling effects and better link the experimental results to the real full-size NPPs, corresponding scenarios were also analysed in the following VVER nuclear power plants: Paks, Loviisa, Dukovany, Mochovce, Kozloduy, and Temelin.

3. WORK PERFORMED AND RESULTS

3.1. PMK experiments

3.1.1. PMK test facility

The PMK-2 facility (Fig. 1) is a scaled-down model of the Paks NPP and it was primarily designed for investigating small-break loss of coolant accidents (SBLOCA) and transient processes of VVER-440/213 plants. The volume and power scaling are 1:2070. Transients can be started from nominal operating conditions. The ratio of elevations is 1:1 except for the lower plenum and pressurise. The six loops of the plant are modelled by a single active loop. In the secondary side of the steam generator the steam/water volume ratio is maintained. The coolant is water under the same operating conditions as in the nuclear power plant. The core model consists of 19 electrically heated rods, with uniform power distribution. Core length, elevation and flow area are the same as in the Paks NPP. In the modelling of the horizontal steam generator primary side, the tube diameter, length and number were determined by the requirement of keeping the 1:2070 ratio of the product of the overall heat transfer coefficient and the equivalent heat transfer area. The elevations of tube rows and the axial surface distribution of tubes are the same as in the reference system. On the secondary side the water level and the steam to water volume ratios are kept. The temperature and pressure are the same as in the NPP [2].

3.1.2. PMK experiment descriptions and results

3.1.2.1. PMK experiment definitions

Altogether five experiments and one additional experiment were performed with the PMK-2 facility. They were divided into three different test types.

The main objective of Test 1 was to reproduce the typical phenomena expected to occur during the post-LOCA cool-down procedure for checking the uncertainties in the corresponding EOPs. These phenomena include re-pressurisation of the primary system by HPIS, pressuriser behaviour during refill, effectiveness of pressurise spray from HPIS, pressuriser refill, primary pressure behaviour following each HPIS pump stop, phenomena until equalization of break flow/HPIS flow, effectiveness of secondary bleed and feed, evolution of primary system temperatures with respect to saturation conditions, and possible voiding in upper head and/or SG hot collector and its effect on primary system behaviour. The 0.5 % break was in the down-comer at cold leg elevation. The accumulators were not available, and 3 HPIS were applied with flow rate of 0.042 kg/s. Scram, secondary side isolation and pump coast-down took place at time zero.

Test Series T2 aimed at investigating the effectiveness of the secondary bleed and the primary feed and bleed in reducing the primary pressure to the LPIS pressure without core overheating during a small-break LOCA (7.4 %), investigating the effect of reduced accumulator pressure, studying the effect of the scaling factor and assessing the code capabilities in predicting the scenarios and their phenomena. All T2 tests start by opening of a 7.4 % break in the cold leg with simultaneous initiation of scram, secondary side isolation, pressuriser switch-off and pump coast down. One/two accumulators inject into the upper plenum/down-comer.

The T2.1 experiment simulated a primary 7.4 % LOCA without high pressure injection, the basic question being whether the primary pressure can be reduced to the shut-off head of the LPIS pumps. Earlier PMK-2 tests indicated that it might be too late to start F&B at superheated core outlet temperature if the accumulators are no longer available. The loss of primary coolant may lead to core overheating before the system pressure decreases to the LPIS operating pressure. Tests T2.2 and T2.3 were follow-up test of T2.1, T2.2 investigating whether pressure reduction is efficient enough using F&B interventions, and T2.3 (counterpart test with PACTEL with reduced initial pressure of 7.7 MPa) investigating the efficiency of reduced accumulator pressure (3.5 MPa) and increased level in reaching the LPIS pressure.

Test T3.1 simulated a rather large 30 % LOCA during a cool-down state of the plant. According to the original cool-down procedures no ECCS could be automatically activated below 2.5 MPa, and this might lead to core heat-up. The test investigated whether a single LPIS train started by the operator – as now foreseen in the Paks NPP – can effectively prevent core heat-up. As a consequence of the large break size the pressuriser was emptied in a few seconds and N_2 entered the primary circuit. The new FZR void probes made it possible to track the nitrogen along the circuit. The secondary side was isolated and the pressuriser heaters were switched off at time zero.

Test T3.2 was originally planned to be run only by the PACTEL facility, but towards the end of the project, it was decided that the test should also be run by PMK (voluntarily) in order to produce a better pair of counterpart tests than Test T2.3. It simulated a 7.4 % LOCA without HPIS, investigating whether the pressure can be reduced effectively without core overheating. It differed from Test T2.1 in that the secondary bleed was not present. Heat transfer in the steam generator and its effect on the transient was of special interest since the secondary side pressure was not reduced. The test was started from lowered initial pressure (7.7 MPa) by opening the break in the down-comer with simultaneous initiation of scram, steam line and feed-water isolation, pressuriser heater switch-off, and pump coast down. One accumulator injected to upper plenum, and two to down-comer. There was no secondary bleed, but the primary bleed was started at $T_{wall} > 500\ ^oC$.

3.1.2.2. PMK experiments – results

Test T1 – results

The primary and secondary pressure histories were typical (Fig. 2). HPIS could not fully compensate the break flow, although it slowed down the pressure decrease considerably. The steam generator relief valve opened and closed during the early part of the transient. The secondary bleed reduced cold leg temperatures and sub-cooling. Stable natural circulation in the primary loop after pump coast-down existed until the end of the transient, and was somewhat enhanced by the secondary bleed. The coolant level behaviour in the pressuriser was mainly influenced by HPIS injection, pressuriser spray, secondary bleed, and boiling in the reactor vessel upper head. Each time a HPIS pump was stopped, it took some time until the break flow decreased below HPIS flow leading to substantial loss of primary inventory. The primary coolant levels were quite stable most of the time. Intensive flashing began in the vessel upper head during the late phase of the transient, resulting in a third fill-up of the pressuriser. The SG collector levels also showed some voiding after 5000 s. However, the core outlet and upper plenum sub-cooling remained clearly positive all the time.

The pressuriser refill was faster than expected, and the pressuriser spraying was not as effective as predicted. Stopping HPIS pumps affected the system pressure and behaviour. The secondary bleed had a small influence on the overall primary system behaviour as was foreseen, although it had an effect on cold leg sub-cooling. The primary system sub-cooling was sufficiently high throughout the transient.

Test T2 – results

The primary pressure behaved normally in all tests (Fig. 3). After a fast sub-cooled blowdown, accumulator injection dominated the primary pressure history. The first and second sharp drops before and after 500s were consequences of the hot leg loop seal fill-up by accumulator water. After emptying of the accumulators there was a slight increase in the pressure, and the maximum value was reached, when the hot leg loop seal was finally cleared. A slow pressure decrease continued then until the end of the transient. Due to several sharp and deep sinks in the coolant level, however, mild heat-ups occurred several times (Fig. 4). The core was re-flooded quickly each time. After the accumulators had emptied a heat-up occurred again. The secondary bleed in T2.1 started at about 1550s, while in T2.2 it was started by the operator already before 900 s. However, in both tests the temperatures continued increasing. When cladding temperatures reached 500 and 300 °C in T2.1 and T2.2 respectively, primary bleed was started, but the cladding temperatures reached 600°C leading to core power shut-off. The LPSI rewetted finally the core.

Tests T2.1 and T2.2 confirmed the expected tendencies that neither the secondary nor the primary bleed is effective enough to reduce the pressure effectively enough, even if their earliest possible actuation is envisaged. This is the consequence of the relatively low primary coolant inventory when these actions are initiated. So the LPIS could not be started in time to avoid severe core heat-up and the core power had to be cut in both tests. In T2.3, due to the lower accumulator pressure, the accumulators emptied much later (after 1800 s), and the prolonged heat-up was delayed. When the cladding temperatures reached 350 and 400 °C, the secondary and primary bleeds were started. As a result, the primary pressure dropped to the LPIS pressure at about 3500 s and the core was re-flooded. The maximum temperature barely exceeded 450 °C. Although core heat-up started also in this test, the secondary and primary bleed actions were effective in reducing the primary pressure to 0,7MPa, and the LPIS injection rewetted the core. So the T2 tests confirmed the beneficial effect of reduced accumulator pressures. They also indicated that the time window between secondary and primary bleeds foreseen in the EOPs may be too short.

Test T3.1 – results

The break size was quite large, and the transient was fast. The pressuriser was emptied at 8s and the primary pressure reached 0.5 MPa in 150 s. The coolant level sank to the hot leg elevation in less than 100 s, and the hot leg and cold leg loop seals were cleared at 150s and 1500 s, respectively. The reactor vessel coolant level reached its minimum value of 1.5 m before 1800 s. A dry-out occurred at about 1300 s (Fig. 5). The maximum cladding temperature was about 400 °C. Just before 1800 s, the LPIS pump was started by the operator. As the water level reached the cold leg elevation significant oscillations occurred in cold leg and break flow due to void fraction changes at the break. After the LPIS activation the primary pressure remained nearly atmospheric. It was an important finding that a single LPIS pump (injecting into the down-comer), started by the operator within half an hour, could effectively refill and re-flood the core.

It was a further objective of this test to study the propagation of N_2 entering the primary circuit from the pressuriser using special void probes provided by Rossendorf [3]. The electrode of these probes is replaced by a micro-thermocouple. In this way they are able to detect the phase (liquid/gas) and to measure the temperature at the same location. This made it possible to distinguish portions of sub-cooled gas from sub-cooled liquid and visualise the processes. First some nitrogen was coming from the pressuriser and entering the primary circuit through the pressuriser surge line. The gas was transported by the main coolant flow towards the steam generator. Finally, it was discharged together with the coolant through the break. After pump coast-down nitrogen could also escape into the reactor vessel. A probe at the inlet of the core showed that there was no significant void fraction during the entire transient, i.e. neither nitrogen nor steam could reach the lowest circuit positions. By 240s most of the nitrogen had left the primary circuit. In this experiment transition from sub-cooled gas-liquid two-phase flow to a saturated mixture could be detected clearly at about 220 s.

Test T3.2 – results

After the fast sub-cooled blow-down, accumulator injection dominated the primary pressure behaviour. Filling up the hot leg loop seal at 400s caused the first temporary pressure increase, and emptying of the accumulator caused another at 650 s. After that the pressure decreased slowly. Due to the sharp and deep sinks in the coolant level, core heat-ups occurred several times, with peak temperatures around 300 °C (Fig. 6). Each time the core was quickly re-flooded. After 800 s the break flow changed to single phase steam, and the coolant level kept decreasing slowly. A severe core heat-up started after 1500 s. Primary bleed was started at cladding temperatures of 500 °C, but it was not very effective. The core power was cut off after 2100 s, when the cladding temperatures exceeded 550 °C. The results of T3.2 were quite similar to T2.1, although the core heat-up started later. Lack of secondary bleed did not have a significant effect. Comparison to the PACTEL counterpart test is discussed in C.2.2.4.

3.2. PACTEL experiments

3.2.1. PACTEL test facility

The reference reactor of PACTEL is the VVER-440 power plant in Loviisa. The PACTEL facility simulates the major components and systems of the reference PWR during postulated small- and medium-break LOCAs and operational transients [4]. The facility consists of a primary system, the secondary side of the steam generators, and the Emergency Core Cooling Systems (ECCS). The reactor vessel model consists of a u-tube construction including down-comer, lower plenum, core, and upper plenum. Volumetric scaling (1:305) was the basic scaling approach in the PACTEL design. The component elevations of the loop are the same as in the reference reactor. Volumetric scaling requires that all the components and piping volumes have to be equally proportional to the respective volumes of the reference reactor. This scaling ensures that the same relative amount of coolant is available for the energy exchange in both systems and preserves the real time scale of the events. Precise conservation of the system component heights and elevations is important for SBLOCA and transient simulations. During these transients, the fluid is in a two-phase state, and the flow processes are gravity dominated. Under gravitational forces, the vapour and liquid phases easily separate, and these separation effects can dominate both thermal and hydraulic characteristics of a transient. Because of this, the elevations in the PACTEL facility are the same as in the reference reactor. However, the volumes of the secondary sides of the steam generators are not in scale due to the attempt to increase the height of the tube bundle closer to the reference steam generator. The volumes of the components have been scaled down by the ratio of 1:305. The exceptions are caused by the use of standard pipe sizes. The core geometry corresponds to the reference reactor geometry.

3.2.2. PACTEL experiment descriptions and results

3.2.2.1. PACTEL experiment definitions

Experiments T2.1, T2.3 and T3.2 were performed using both test facilities, PMK and PACTEL, and their definitions correspond to those of the PMK tests. The first one (T2.1) was started from different initial conditions (initial pressure 12,3MPa in PMK and 7,7MPa in PACTEL), but for the other two experiments the specified initial and boundary condition were (almost) the same, making them "counterpart tests". The additional voluntary PMK experiment T3.2 was carried out because the T2.3 experiments missed some of their objectives related to the similarity of the tests. The heat losses of the facility [5] in its current configuration were defined by carrying out special heat transfer tests, developed on the basis of information from PKL, BETHSY and PSB VVER. The advanced FZR void probes were used in all PACTEL tests [6].

3.2.2.2. PACTEL experiments – results

The analysis of the heat loss experiments gave a value of 85 kW for the total primary loop heat losses at 260 ^{o}C without the pressuriser (Fig. 8). A value of 7.2 kW was calculated for the singular heat losses, and 28.5 kW for the primary pumps. Thus, heat losses through the insulation should be about 49.3 kW. The pressuriser heat losses would be about 3.5 kW at operation temperature. A characterising test was also performed at PACTEL. The test was a simple coolant inventory reduction test (after a long steady state period), including a transition from forced flow to natural circulation flow.

In T2.1 the primary pressure first decreased rapidly to the level of secondary pressure (Fig. 9). Accumulator injection started at 5.5 MPa. Injection flow was rather smooth, except that the injection stopped for a few seconds when the primary pressure was close to the secondary. Due to accumulator injection the upper plenum temperature dropped to 130 ^{o}C, but recovered after the accumulators were emptied and injection stopped. Also the primary pressure recovered somewhat, but the pressure behaviour was very smooth. During the remaining transient primary pressure and water level decreased slowly. The first heat-up started at about 900 s (Fig. 10). The clad temperatures reached 350 ^{o}C at 1150 s, and secondary bleed started at 1230 s. LPIS started at 1290 s and the core cooled down. Primary bleed was not started since the core temperatures stayed below 450 ^{o}C. Secondary bleed and LPIS were initiated almost simultaneously, the former having practically no effect on the transient. Decay power in the test was somewhat lower than specified.

In T2.3 the primary pressure stayed longer close to the secondary than in T2.1 (Fig. 9) because the accumulator pressure was lower than secondary pressure, and the accumulator injection did not start before 3.5 MPa. After accumulator injection stopped, the primary pressure recovered a little. The upper plenum temperature had dropped to 100 °C. Slightly incorrect accumulator initial levels caused some atypical pressure behaviour. There was a minor core heat-up at 800 s, but soon the core was cooled again, and the core temperatures stayed below 200 °C all the time (Fig. 10). LPIS was started at 1500 s and filled the primary side. The primary and secondary bleeds did not start at all. An error in the decay power controlling system caused lower than defined (~ 20 kW) decay power in both Tests 2.1 and 2.3. Probably due to the lower decay power the test did not show any core heat up like in PMK. Another difference between PACTEL and PMK was a difference in pump coast down.

T3.2 differed from T2.1 in that the secondary bleed was not present, and the decay heat was higher. Heat transfer in the steam generators and its effect on the transient were of special interest due to the absence of secondary bleed. The transient was quite similar to T2.1, except that the primary pressure stayed higher until about 1400 s and the core heat-up, which started at 1100 s was more severe. Maximum clad temperature reached 490 °C at 1480 s (Fig. 10). The LPIS reflooded the core efficiently. Primary bleed was not started at all.

Experiment T3.2 – Comparison-to-counterpart Test PMK T3.2

The overall system behaviour until emptying of the accumulators was rather similar in PACTEL and PMK. The primary pressure between 100 and 250 s was higher in PMK due to higher secondary pressure. Accumulator injection was continuous in PACTEL, but stopped in PMK at about 400 s, when the loop seals were filled by accumulator water. This was probably due to the loop arrangements differences (three loops in PACTEL and one in PMK), which also have an influence on the break flow, which depends on conditions in one single loop in PMK, but not in PACTEL, where the loop conditions differ from each other. The break flow had a strong impact on the system behaviour after the accumulators had emptied. In PACTEL break flow changed to steam flow quickly, but in PMK loop seal clearing effects were important until 800 s, and the system pressure decreased faster in PACTEL. The end pressure of the accumulators was about 0.3 MPa lower in PACTEL, but the LPIS still started before the cladding temperatures reached 500 °C (starting condition of primary bleed). The main core heat-up started when the core water level was about 0.8 m in PACTEL and about 1 m in PMK below the core top (PMK had several minor heat-ups earlier in the transient). The heat-ups were also affected by the axial power profile, cosine in PACTEL and uniform in PMK. The main core heat-up in PMK was much more severe (Fig. 23).

Overall conclusions

In all PACTEL tests LPIS pressure was reached before the clad temperatures triggered the primary bleed. In T2.3 no core overheating occurred although the accumulator injection was not started before 700 s. In T2.1 and T2.3 the core power was lower than specified due to an error in the controlling system, but in T3.2 this was corrected. According to the sensitivity analyses performed, the core power was an important boundary condition affecting the results considerably. The LPIS pump capacity in PACTEL was higher than the correct scaled value, and the primary circuit was filled up too fast by the LPIS, but did not affect the transients before the LPIS injection phase.

The reduced accumulator pressure and increased level in Test T2.3 resulted in no core heat-up, and the temperature limit for primary bleed was not reached. Accordingly, the most important finding of the PACTEL tests was the observed effectiveness of a reduced accumulator pressure in reaching LPIS pressure and preventing core overheating.

3.3. PMK analyses

The five originally planned PMK experiments were analysed by AEKI, FZR and NRI using the RELAP5/Mod3 and ATHLET1.2 computer codes. Only one pre-test analysis was considered necessary for Test T1, but for the other tests both pre-test and post-test analyses were performed (for the T2 test series 12 calculations, and for the T3.1 test 4 calculations). All in all the analyses contributed significantly to the assessment of the codes in the specific range of application for accident management. Further work recommended to better understand the observed deviations, e.g. in the prediction of mass inventory and nitrogen propagation. The analyses indicated a need to address specific phenomena, like pressuriser spray effectiveness, pressuriser behaviour during refill, and swell level behaviour at low pressures, by more basic separate effects tests. Some IMPAM tests could be repeated with different pump coast-down timings.

3.3.1. PMK analysis results

For Test T1 the primary pressure decrease during pressuriser spraying was slightly lower in the calculation especially at higher pressures (Fig. 11). RELAP5 calculated slower de-pressurisation of the system during pressurise refill. Further investigations are needed for this phenomenon based on separate effect test results. The calculation confirmed that the secondary bleed has little effect on primary system pressure reduction, but affects cold leg sub-cooling. Although the primary system sub-cooling stays high enough, voiding in the vessel upper head and in the SG primary collectors cannot be avoided.

For Test T2.1 AEKI and FZR, pre- and post-test analyses show good overall agreement with the experiment. The RELAP and ATHLET calculations confirmed that the AM measures foreseen are not effective enough to reduce primary pressure fast enough, and substantial overheating of the reactor core can not be avoided (Fig. 12). The step-wise accumulator injection in PMK T2.1 could not be predicted accurately by the codes. When the core started to heat-up, the calculated reactor collapsed level was lower than in the test. In both AEKI RELAP calculations the primary pressure and the RPV water level were well predicted after the accumulator injection phase, but the core dry-out began later than in the test. In FZR ATHLET calculations the primary pressure was well predicted, but the vessel level was lower than in the test. This gave better timing of the core heat-up (Fig. 13). The post-test calculation predicted the timings well. A probable reason for the problems is the over-prediction of swell level at low system pressures by both codes. The break flow was in good agreement with the measurement for the first 300 s, then both codes under-predicted the flow. However, the vessel inventory was not affected much. Only the RELAP calculations showed a slight effect of the primary bleed on the core level and temperature behaviour.

With regard to Test T2.2, the calculations confirmed that even an early actuation of secondary and primary bleed could not reduce the primary pressure to prevent severe core heat-up. All RELAP and ATHLET calculations showed fairly good overall agreement with the experiment. When the core heat-up began, the calculated reactor water level was lower than measured. The early primary bleed caused a temporary core rewetting, which was predicted only by RELAP, but not by ATHLET. RELAP over-predicted the primary pressure slightly, but predicted the vessel level well. The core heat-up in the calculation began much later. The LPIS started during the heat-up, resulting in subsequent rewetting of the core. The maximum T_{clad} was 595 °C. ATHLET under-predicted the vessel level substantially. T_{clad} reached 600 °C before the LPIS pressure was reached. The break flow was under-predicted by both codes in the latter part of the transient, perhaps due to the PMK pump modelling.

For Test T2.3 the specified initial and boundary conditions were somewhat different from the actual test, resulting in problems in interpretation of the pre-test analyses results. Figure 14 shows a comparison between the measured core temperatures and the RELAP pre- and post-test results. The pre-test calculations predicted no core heat-up. At T_{clad} of 350 °C the secondary bleed was started, and at 400 °C the primary bleed. In contrast to Tests T2.1 and T2.2, the LPIS pressure was successfully reached. The post-test analyses were much better than the pre-test analyses. There were differences with regard to the primary pressure, probably mainly due to the effects of the PMK single loop on the step-wise operation of the accumulators. Core heat-up started at a lower water level than measured.

Test T3.1 showed that a single LPIS pump started by the operator within half an hour effectively refilled and re-flooded the core. Three calculations were done using RELAP and ATHLET (only pre-test). RELAP predicted the clad temperatures quite well, although the vessel level was under-predicted. A small core heat-up before 500 s was predicted, but not measured (Fig. 15). The RELAP post-test calculation gave better results for both the timing and magnitude of the core-heat-up. ATHLET predicted the vessel water level quite well, but did not predict any core heat-up. All the codes failed to predict the break mass flow well until the break flow changed to single phase steam, maybe due to the simplified pump models.

3.4. PACTEL analyses

The three PACTEL experiments T2.1, T2.3 and T3.2 were analysed (pre- and post-test) using four different codes: APROS, CATHARE, ATHLET and RELAP5. The important physical phenomena observed in the PACTEL tests were generally well predicted. Correct definition of the initial and boundary condition of the tests proved to be essential in order to get good results. Global parameters (pressures, mass inventory etc) were less sensitive than the fuel clad temperatures. Test T2.3 was carried out with delayed accumulator injection (reduced accumulator pressure), which had a favourable effect on the core cooling, and the PCT remained below 350 °C. This effect was well reproduced by all code calculations. No secondary or primary bleed took were started.

3.4.1. PACTEL analysis results

Figure 16 shows APROS calculations of clad temperatures in Test T2.1 indicating high sensitivity to differences in nodalisation (especially down-comer modelling). ATHLET, CATHARE and RELAP calculations were in good agreement with the measured data, and all important phenomena were present, especially in post-test (Fig. 17). However, there is a peak in the measured break flow in the beginning, which was not predicted by the codes. This peak is probably due to a systematic measurement error (residual water in discharge line). At about 500s after depleting accumulators the break flow turned into steam flow. In all calculations the break was a bit under-predicted. ATHLET had a problem with the calculation of the lower plenum water level, CATHARE slightly over-predicted primary pressure during accumulator injection, and RELAP had some problems after LPIS start. The maximum T_{clad} did not reach the criterion for primary bleed (400 °C) according to both the test and calculations. A stable cool down was achieved without primary bleed.

The results of T2.3 ATHLET post-test analysis were generally in good agreement with the measured data, and all important phenomena were present. Like in T2.1, the main problem with ATHLET had to do with lower plenum water level calculation. In the test no core heat up was observed, but RELAP5 predicted a very small heat up (up to 300 °C) in the beginning. No secondary or primary bleed took place. CATHARE predictions were generally good, but between 500s and 800s there were some problems probably due to strong condensation as a result of accumulator injection. Similarly to T2.1, the break flow was slightly underestimated by RELAP5. After depleting the accumulator the reactor vessel water level was slightly underestimated, although the water level in the down-comer was quite well predicted. No excessive core heat up was observed, and the clad temperatures stayed below 350 °C, indicating that delayed accumulator injection is beneficial.

ATHLET, CATHARE and RELAP5 pre- and post-test analyses were in quite good agreement with the measured data, and all important phenomena were present. The main problems concerned the rather large oscillations (mass flows, temperatures, etc) during accumulator injection. The LPIS pressure was again reached without operator intervention. The maximum T_{clad} stayed below 480 °C, and the primary bleed was not started. Although T2.1 and T3.2 specifications were the same until core heat-up, there were differences in the tests due to the different core decay power and initial accumulator conditions. RELAP5 over-predicted the primary pressure reduction rate, and under-predicted the time of HA depletion. As with T2.1 and T2.3 the break flow was slightly under-estimated. Afterwards the reactor-vessel water level was slightly under-predicted, but the down-comer water level and the core heat-up timing were quite well predicted. The maximum T_{clad} was under-predicted by about 100 °C. ATHLET over-predicted, and RELAP5 under-predicted the core heat up timing. Both under-predicted the maximum clad temperature by about 100 °C, but CATHARE predicted both the value and timing quite well.

3.5. Nuclear power plant analyses

In order to establish a realistic connection between the experiments + their analyses and real VVER power plants, several analyses of VVER plant transient scenarios corresponding to the PMK and PACTEL experiments were performed. After all, the main objective of the project was to investigate whether changes in the operational practices of the VVER nuclear power plants should be considered.

The following V440 NPPs were included in the study: Mochovce, Kozloduy, Loviisa, Paks and Dukovany, and the following V1000 NPPs for additional comparison: Kozloduy and Temelin. The following computer codes were used: Mochovce, Kozloduy V440, Temelin V1000 and Dukovany analyses were performed with RELAP5, Loviisa and Paks analyses with APROS5, and Kozloduy V1000 analyses with CATHARE2.

3.5.1. An example of analyses corresponding to Test 1

The Mochovce analysis is presented, but the other Test T1 related NPP analyses performed lead to similar conclusions. The transient is initiated by opening a 32 mm break in the "pressuriser loop". A loss of offsite power is assumed and all main coolant pumps are coasted down, and later a turbine trip is assumed. First primary pressure decreases, three HPI pumps start at 109 s, and primary pressure decrease is stopped. Pressuriser-level decreases and HPIS initiation stops the pressuriser level drop at 3 m at 109 s. The secondary pressure rapidly increases to 5.45 MPa at 10 s. All of the steam dumps to atmosphere (BRU-A) stay opened for about 140 s. Break flow rate is first 69 kg/s and then mainly depends on HPIS injection.

At 1500 s the operator opens a redirected make-up train to spray the pressuriser, to increase pressuriser level, and to reach the stopping conditions for one HPI pump (level > 6.0 m and sufficient sub-cooling after 1900 s). At this time the pressuriser level is 2.45 m and actual sub-cooling is 84 °C, while the sub-cooling margin required for first HPI pump stop is 28 °C. The first HPI pump stop can be stopped at 1900s. The operator starts secondary bleed at 1800 s keeping the maximum allowed primary cool-down rate below 55 °C/h. The second HPI pump is not stopped until 5389s. Then the pressuriser level is 6.0 m and sub-cooling is 74 °C. Stopping of the second HPI pump depends on the operator since the required conditions had been met 40 min earlier. The last HPI pump is stopped at 9540 s when RPV outlet temperature is below 155 °C, pressuriser level 6.0 m and maximum make-up flow rate is established. Stopping of the last HPI pump leads to gradual pressuriser level decrease. Primary circuit is depressurised by the pressuriser PORV, pressuriser level starts to rise and remains stabilised above 6m. After that the break mass flow rate equals the make-up system flow rate (25 kg/s). When comparing to PMK Test T1, the NPP analysis predicted a slow pressuriser level decrease, but T1 showed a level increase in the beginning. Also, NPP calculations indicate that spraying is more effective than the test demonstrates. The primary system sub-cooling is sufficiently high in both the test and the NPP analysis (Fig. 19). The NPP analysis suggests that a sufficiently high pressuriser water level is most important for reaching the conditions to stop the individual HPI pumps.

The NPP analysis indicates that the current Mochovce NPP EOPs provide an appropriate strategy for a post-LOCA cool-down procedure. It is possible to depressurise and cool-down the circuit without getting primary coolant saturated. The secondary bleed influences the time when the primary sub-cooling condition for third HPI pump stop is reached.

3.5.2. Examples of analyses corresponding to Test Series 2

Two examples of analyses are presented, one (Dukovany) addressing a 136 mm break and the other (Loviisa) addressing a 32 mm break. The smaller 32mm breaks were analysed because they presented more severe challenges to the NPPs and their ECC systems. The other Test Series 2-related analyses lead to similar conclusions.

3.5.2.1. Dukovany calculation related to Test T2.3

The transient is initiated by opening a 136 mm diameter break (7.4 %) in the cold leg. No HPIS is available, and the operator depressurises the system. The rather large break size leads to a fast decrease of the primary pressure and pressuriser level. Steam is quickly formed in the reactor upper head and expands very fast downwards to outlet nozzles elevation. An additional assumption – the loss of offsite power – leads to a trip of main coolant pumps, stop of the make-up system etc. The reactor is consequently shut down from the SCRAM signal “trip of 4 or more RCPs”. The pressure decrease slows down when reaching the secondary pressure (at 50s). At 170 s reactor mixture level drops under the outlet nozzles, primary circulation stops, heat transfer at SGs reverses (230s), and primary pressure decrease under secondary pressure. The first small core uncovery occurs between 180 and 230 s (PCT 320 °C). At 270-385 s, a second larger core uncovery occurs with a PCT of 490°C (Fig. 20). However, the maximum core outlet temperature is “only” 339 °C meaning that the operator should not start the secondary bleed.

Accumulator injection starts at 360 s, leading to complete core recovery and filling up of the down-comer. The accumulators are empty at 520 s and the primary inventory starts to decrease again. The mixture level stabilises at the top of the core, and the heat-up remains small at 700 s with PCT of 325 °C. The pressure continues to decrease, and the LPIS starts at 1407 s when the core is still covered. The reactor mixture level slowly increases up to outlet nozzles (at 1800 s) and core cooling is ensured. The agreement between PACTEL Test T2.3 and the Dukovany analysis is quite good, although the calculated temperature peaks are somewhat higher than measured.

It can be concluded that in this there was no major core heat-up and no operator actions were needed. A case with smaller break (60 mm) was also calculated. In that case the unavailability of HPIS would lead to core damage without operator interventions, but the operator can prevent core overheating by starting secondary bleed in time.

3.5.2.2. Loviisa calculation related to Test T2.3

A 32-mm-diameter cold leg break was analysed. The assumptions included the unavailability of HPIS, the accumulator pressure of 3.50 MPa, and the criterion for starting secondary bleed at 370 °C and the primary bleed at 550 °C core outlet temperature. It was also assumed that the operator opens both steam-dump valves (BRU-A) as soon as the core exit temperature rises to 370 °C. This action results in fast primary pressure drop with flashing in the pressure vessel. The core mixture level rises and core exit temperature becomes saturated. Soon the core collapsed level drops again and the core exit temperature begins to rise. However, the accumulator injection begins soon and the core is rapidly covered. The LPIS pump injection begins before the accumulator injection stops. Primary F&B is not needed since the core exit temperature does not reach 550 °C (Fig. 20).

Comparison between this calculation and PACTEL Test 2.3 is difficult due to the different break sizes (1.5 % break in Loviisa and 7.4 % in PACTEL). In the analysis the operator opens both steam dump valves to decrease the primary pressure fast. Without the operator action core, heat-up would probably occur.

3.5.3. An analysis corresponding to Test Series 3

Only one Test Series 3-related NPP transient was analysed, namely a small break (D 80 mm) in a cold leg of the Mochovce NPP, but several different cases were calculated. The small-break size of D 80 mm was selected, because the size used in the test (corresponding to D 136 mm in the NPP) leads to "too" efficient depressurisation of the primary circuit and the core outlet temperature does not reach the value for the secondary bleed, and the LPI pumps start to inject already at 1260 s without any operator action. The LPIS, but no HPIS, and three accumulators were assumed to be available.

In case A, secondary bleed with maximum cool-down rate of 30°C was assumed. The core outlet temperature exceeded 370 °C after 3000 s and the secondary bleed was started. The LPIS pressure was reached before 3500 s. Soon the core outlet temperature exceeded 550 °C, and the primary bleed was started. The PCT 1157 °C was reached at 3500 s, but before 4000 s it was below 200 °C (Fig. 21). In case C no maximum secondary cool-down rate was specified, and the transient was very similar to case A. The PCT was 1146 °C.

In case B, no secondary bleed was assumed, but the transient was very similar with case A until core heat-up started. The PCT 1200°C was reached later at 4000s. Cladding temperatures dropped below 200°C before 5000 s. In this case heat was transferred from the secondary to the primary side after the secondary bleed start (in contrast to the other cases).

In case D, the assumptions were the same as in case C, except that the secondary bleed was started earlier, when the core outlet temperature exceeded 330 °C at about 2800 s. The LPIS pressure was reached a bit earlier, the core outlet temperature did not exceed 550 °C, and the primary bleed was not started at all. The PCT 911 °C was reached before 3400 s and 200 °C only 40 s later.

3.5.4. VVER-1000 analyses

Some VVER-1000 NPP analyses related to IMPAM-VVER experiments were performed. Two break sizes were considered: 163 and 231 mm. The break was assumed to be horizontal, located in the loop with the pressuriser between the vessel and the coolant pump. The boundary conditions corresponded to Tests T2.1 and T3.2.

Two Temelin VVER-1000 NPP cases corresponding to experiments T2.1 were analysed using RELAP5. Both cases were cold leg break LOCAs without HPIS, one with a D163mm break and the other with D 231 mm. In case of the larger break, there was no core heat-up. In the other case a 120 s long core heat-up occurred before the accumulator injection started. However, the temperature increase was so small that there was no need for operator actions (depressurisation of the system). The peak cladding temperature (PCT) was only 345 °C.

Two Kozloduy VVER-1000 NPP main cases corresponding to experiments T2.1 were analysed using CATHARE2. Both cases were cold leg LOCAs without HPIS, one with a D 163 mm break and the other with D 231 mm. In case of the larger break without operator actions, a 50 s long core heat-up occurred before the accumulator injection started. However, the core temperature increase was so small that there was no need for operator actions (depressurisation of the system). The PCT during was only 383 °C. Another D 231 mm break, but with operator actions was also analysed. A secondary bleed with fast cool-down and moderate primary bleed was effective and no core heat-up occurred. The used fast secondary bleed was excessive, and a cool-down mode with 60 °C/h seems more appropriate.

In case of a Kozloduy VVER-1000 NPP D 163 mm break without operator actions, three rather short core heat-ups occurred, the first one before the accumulator injection started. Even in this case the heat-up was small and the PCT was only 433 °C (Fig. 22), and there was no need for operator actions. Another D 163 mm break with primary/secondary bleed was analysed. In this case no core heat-up occurred and the PCT was 345 °C. However, the results again indicate that the secondary de-pressurisation rate was excessive, and 60 °C/h would be sufficient.

Another Kozloduy V-1000 NPP D 163 mm break, corresponding to Test T3.2, with early primary bleed resulted in about 20s earlier safety injection, resulting in a decrease of PCT by about 40 °C, and a plant recovery improvement without secondary bleed. The PCT was 391 °C.

From all the V-1000 cases analysed, it can concluded that a 7.4 % cold-leg LOCA in a V-1000 NPP behaves qualitatively quite similarly to that of VVER-440. Due to the differences e.g. in the reactor power, the pressure and the geometry, the core heat-up occurs earlier and is stopped by accumulator injection. Both analysed break sizes assure fast enough de-pressurisation that the LPIS pressure is reached without any operator actions. The operator actions improve the plant recovery even further. The codes CATHARE2 and RELAP5 predict very similar NPP behaviour. The results still indicate a need for further studies for the modelling of reflooding from the upper plenum.

3.5.5. Conclusions of all NPP analyses

From the results of the NPP analyses (four different NPPs) corresponding to PMK Test T1, it can be concluded that the current NPP EOPs provide appropriate strategies for post-LOCA cool-down procedures. It seems to be possible to depressurise and cool down the primary circuit without getting the core saturated. The secondary bleed influences the time when the primary sub-cooling condition for the last HPSI termination is satisfied. Without the use of make-up system the HPSI cannot be terminated, and the pressure remains above the LPSI pressure.

With regard to the NPP analyses corresponding to Test Series T2, it can be concluded that, although the applied EOPs are different, the NPP transients with similar break sizes turn out to be quite similar. The break size D 136.5 mm is large enough to ensure a rapid primary pressure decrease to the LPIS pressure without operator actions. The smaller break size D60mm also assures quite rapid depressurisation, but depending on the LPIS design in some plants, it is not always possible to reach the LPIS pressure without operator actions. A secondary bleed can prevent primary bleed start. The secondary bleed is more effective with maximum flow rate and leads to more effective LPIS injection. Earlier start of the secondary bleed leads to a lower PCT and a faster core recovery. If the HPSI is unavailable, the secondary bleed should be started as soon as possible. The temperature increases very fast after core uncovery. The time between the secondary and primary bleed starts is very short. A lower accumulator pressure (3.5 MPa instead of 5.9 MPa) seems to be beneficial and lead to more effective core cooling.

The Test 3.2-related analyses show that the secondary bleed has no effect on the time of the LPIS injection start. The secondary bleed helps to retain the primary pressure close to the LPIS pressure, and the LPIS supply is sufficient to stop the core heat-up. Effective start of the secondary bleed leads to more effective LPIS injection, earlier cladding temperature drop and core recovery. Earlier secondary bleed start leads to a lower PCT, and a faster core recovery. Due to different break sizes the results of Test 3.2 and the NPP calculation cannot be compared directly.

Overall, rather good agreement was reached between the experiments and the NPP calculations, although the scaling factor and the test facility design (e.g. number of loops) have a significant effect on the results (see the next chapter C.5.6). VVER-1000 analyses indicated that a LOCA with the same relative break size as in V-440 results in lower temperatures in the core (without operator intervention).

3.5.6. Scaling study

A scaling study was performed in order to compare the experimental and analytical results obtained in this project using the scaled-down facilities PACTEL and PMK-2 with the corresponding analytical predictions of full-scale nuclear power plants (NPPs). Such comparison addresses the extrapolation from reduced scale to full scale using thermo-hydraulic computer codes, which have mostly been validated by utilising reduced scale facilities. From the practical point of view the study addresses the following question: “Can we use the available computer codes with confidence to predict the behaviour of full-scale NPPs during hypothetical transients and accidents?”

Comparing to reduced-scale simplified experimental facilities, real NPPs represent much more complex and complicated systems in addition to their size. Differences between the experimental facilities PACTEL and PMK-2 and real VVER-440/V213 NPPs concern e.g. the size (3-D effects), the number of loops, heat capacities and the related heat losses, core power and maximum primary pressure. So it is obvious that the behaviour of a full-scale NPP in a hypothetical transient or accident is different from the behaviour of a scaled-down facility in a corresponding experiment.

A concrete example of a comparison between reduced and full-scale results is presented for PACTEL and PMK Test T2.1 and a corresponding scenario analysed with the RELAP5-3D code for Bohunice V2 NPP, equipped with two VVER-440/V213 reactors. For this purpose the initial and boundary conditions applied in NPP analysis were adjusted to the experimental scenario as closely as possible – even if this adjustment does not comply completely with the reference state of the NPP (e.g. linear coast down curve for RCPs) or allowed operational regimes. This is the main difference contrary to other NPP analyses performed in the IMPAM-VVER project, where the experimental scenario was adjusted to concrete NPP conditions (which may be different for Loviisa, Dukovany, Paks, Mochovce or Kozloduy NPP). The main goal in these NPP analyses was to assess the correctness of existing EOPs. To fulfil this goal, in some of those analyses the break diameter was even reduced from 136.5 mm (corresponding to the break used in both experimental facilities) to 60 mm, a break size more convenient for demonstration of EOP strategies. In these cases the experimental results were used more or less for demonstration of correctness of chosen accident management strategies rather than for direct comparison with the results of the corresponding NPP analyses.

The following PACTEL Test T2.1 related results are compared: measured test results, calculated results using RELAP5-3D, calculated results of a corresponding scenario in Bohunice V2 NPP using RELAP5-3D, and also the measured results from the corresponding PMK-2 test, which was a kind of counterpart test to the PACTEL test, but not a very good one. The initial and boundary conditions for PMK-2 were a bit different. The nominal initial pressure and rated power were used. The power, primary flow rate, primary temperatures, and secondary and accumulator pressures were higher than in PACTEL. Also the single/triple loop design difference of the two facilities led to differences especially during the accumulator injection phase.

In general, in the post-test analyses the overall behaviour of the experiments performed on both facilities was well predicted. This was not always the case in the pre-test analyses. The main reason is probably the fact that the experiments were very sensitive to the boundary conditions. E.g. in the case of PACTEL, one of the most important boundary conditions, the decay heat used in the pre-test analyses did not accurately correspond to the real one. Therefore sensitivity studies on core power definition were performed in post-test analyses improving the results considerably. This, in general, indicates the importance of sensitivity studies in accident analysis of NPPs.

Rather good agreement was reached between the PACTEL Experiment 2.1 and the RELAP5-3D post-test analysis. This was also the case for the other IMPAM-VVER participants, who were using different computer codes. This tends to confirm the applicability of these computer codes to such kind of scenarios, representing typical accident management strategies used for VVER-440 reactors. However, the collapsed water level in the reactor vessel was generally under-predicted and the start of core heat-up was predicted at a lower core level than measured.

Quite good agreement was also reached between the PACTEL experiment and the analytical results obtained for the full-scale NPP case. All the main phenomena were reasonably well predicted. This result tends to confirm that the experimental results and the proposed operator strategies (secondary bleed) are applicable to VVER-440/V213 NPPs.

Some differences in the pressure behaviour between the PACTEL test and the NPP calculations were found early in the transient before the accumulator injection started. In the NPP case there was faster pressure drop, and consequently, earlier start of accumulator injection than in the test. This is probably due to the higher ratio of wall capacities to coolant volume and the larger heat transfer area between coolant and the walls in the facility, which increased the heat transfer to the coolant and slowed down the pressure decrease.

However, the main differences between the PACTEL experiment and the NPP analysis results occurred during the accumulator injection phase. In the NPP case the predicted water level in reactor was significantly higher than in the test. This may be due to the following reasons: The PACTEL reactor vessel is about 1.35 m lower than the real VVER-440 reactor vessel, thus influencing the differences between water levels; there is more steam condensation in the upper plenum in the NPP calculation due to quasi 3-D flow effects resulting from different upper plenum nodalisations. In the PACTEL analysis, the single “dead-end” vertical pipe presented the upper plenum. The German UPTF tests have shown that the behaviour of the coolant in the upper plenum and the core are highly three-dimensional. The PACTEL and PMK facilities are too small to model these phenomena.

When comparing the experimental results with the NPP calculation, it is difficult to separate the causes of the differences (different scales, geometrical arrangements and initial and boundary conditions). However, some conclusions can be made. E.g. from the course of the primary and accumulator pressures it seems that the scaling factor has a significant influence on the accumulator injection and on the course of the primary pressure. In smaller facilities the injection phase is longer and the drop of the primary pressure is slower than in larger facilities or NPPs.

Overall, although the presented experimental and analytical results do not differ very much from each other qualitatively, it can be concluded that the scaling factor has a significant influence on the results (see e.g. Fig. 23).

4. CONCLUSION

The objective of PMK Test T1 was to reproduce all the major phenomena occurring during a post-LOCA cool-down of a VVER-440 NPP and check the uncertainties in the applicable EOPs. The effect of pressuriser spraying was over-predicted, and the pressuriser refill rate under-predicted by RELAP5 (Fig. 11). Although the secondary bleed affected cold-leg sub-cooling, it did not noticeably affect the primary system pressure. The primary system sub-cooling remained sufficiently high throughout the transient.

The VVER-440 NPP analyses were consistent with PMK Test T1 and confirmed that the current NPP EOPs provide appropriate strategies for post-LOCA cool-down procedures. It seems to be possible to depressurise and cool down the primary circuit without getting the core saturated.

The Test Series T2 simulated LOCAs without HPIS to investigate whether the primary pressure can be reduced to the LPIS pressure before core overheating occurs. PMK Tests T2.1 and T2.2 (Fig. 4) showed that an early secondary or primary bleed was ineffective in reducing the pressure sufficiently, and the LPIS could not be started in time to avoid severe core heat-up. However, in PACTEL Test 2.1 (Fig. 10) the LPIS pressure was reached early enough and the PCT remained well below 400 ^{o}C.

In PMK Test T2.3 (Fig. 4) no severe core overheating occurred (max. about 450 ^{o}C), and in PACTEL Test T2.3 (Fig. 10) even no core heat-up (partly due to the lower than specified core power). The overall improvements in depressurisation and core cooling can be attributed to the reduced accumulator pressures (3.5 MPa).

With regard to the PMK Test Series T2 there were some differences between the calculated and measured primary pressures during accumulator injection. The step-wise operation of the PMK accumulators could not be predicted. When the core started to heat up, the calculated reactor collapsed level was lower than measured. In RELAP5 calculations the reactor vessel collapsed level was quite well predicted after accumulator injection, but still core heat-up occurred too late. ATHLET predicted too low vessel collapsed level, but still quite good timing for core heat-up. Only the RELAP5 calculations show some effect of the primary bleed on the core behaviour. In Test T2.2 the early primary bleed causes some increase in the vessel coolant level and a temporary core rewetting, predicted by RELAP5 but not by ATHLET. All the codes fail to predict well the loss of primary mass inventory until the break flow changes to single-phase steam. This may be due to the simplified pump models.

With regard to the PACTEL Test Series 2 analyses generally, the important physical phenomena observed were quite well predicted by the codes. Correct definition of the initial and boundary condition of the tests proved to be essential in order to get good results. In the calculation of PACTEL Test T2.1, CATHARE and RELAP5 produced good results for the core heat-up. ATHLET over-predicted the PCT in the pre-test calculation, but did quite well in the post-test calculation. APROS sensitivity studies showed the sensitivity of the results (e.g. core heat-up timing and magnitude) to the choice of nodalisation (especially down-comer modelling) (Fig. 16). Test T2.3 was well predicted by all calculations. No secondary or primary bleed were started.

Although the applied EOPs are different, NPP transients corresponding to Test Series T2 with the same break sizes turned out to be quite similar. However, the break size D 136.5 mm was too large to challenge the EOPs, and the LPIS pressure was reached quite rapidly. On the other hand, a break size of D 60 mm caused problems. In some plants the LPIS pressure could not be reached effectively without operator actions. A secondary bleed could prevent the primary bleed initiation, and was more effective with maximum flow rate, leading to more effective LPIS injection. Earlier start of the secondary bleed resulted in a lower PCT, as well as a faster core recovery. The temperature increased very fast after core uncovery. A lower accumulator pressure (3.5 MPa instead of 5.9 MPa) seems to be beneficial. VVER-1000 analyses show that a LOCA with the same relative break size results in lower temperatures in the core than VVER-440 (without operator intervention).

The objective of PMK Test T3.1 was to investigate the effectiveness of an operator action to start the LPIS pumps if a major LOCA would occur during plant cool-down. The test proved that a single LPIS pump, started by the operator within half an hour and injecting into the down-comer, effectively refills and refloods the core. The advanced void probes provided and installed by FZR allowed tracing N_2 propagation throughout the primary circuit. ATHLET pre-test analysis by NRI predicted the vessel level quite well, but still calculated no core heat-up. RELAP5 calculated the timing of core heat-up correctly, but with a too low vessel level. RELAP5 predicted the tendencies in nitrogen propagation around the circuit fairly well (but timing not so well).

Test 3.2 was quite similar to Test 2.1 except for the lower initial pressure and lack of secondary bleed. It was finally performed by both PACTEL and PMK in order to have a better counterpart test pair than T2.3. The overall system behaviour of both facilities was quite similar until about 650 s when the accumulators emptied. However, the scaling effect and the effect of different facility designs (3 loops versus 1 loop) resulted in important differences, especially later in the transient. The system pressure decreased faster in PACTEL and the primary bleed was not initiated. In PMK the loop seal clearing affected the break flow and slowed down the depressurisation rate. In PACTEL the core heat-up started at about 1200 s and in PMK considerably later, after 1500 s. Lack of secondary bleed did not have a significant effect. The peak clad temperature in PACTEL Test T3.2 was under-predicted by all codes, except by CATHARE (post-test), which also predicted the timing well. RELAP5 calculated too early and ATHLET too late core heat-up.

Overall, both the experiments and test/NPP analyses confirmed the beneficial effect of reduced accumulator pressures in preventing core overheating, and indicated that the time window between secondary and primary bleeds foreseen in the current EOPs may be too short. If the HPSI is unavailable, it seems that the secondary bleed should be started as soon as possible.

The computer code analyses contributed significantly to their assessment in the specific range of application for accident management. Further work is needed to better understand the observed deviations, e.g. in the prediction of mass inventory and start of core heat-up, as well as nitrogen propagation. The analysis pointed out the need to address specific phenomena, like pressuriser-spray effectiveness, pressuriser behaviour during refill, and swell-level behaviour at low pressures, by more basic separate-effects-type tests. Some IMPAM tests could be repeated with different pump coast-down timings.

Although the experimental and analytical results, including the NPP calculations, do not differ very much from each other qualitatively, it can be concluded that the scaling factor and the facility design (e.g. number of loops) have significant influence on the results (see e.g. Fig. 23).

Although this project produced a lot of useful information, it alone does not provide a sufficient basis for any individual NPP for changing its EOPs. Consequently, it is recommended that more investigations be carried out by the VVER utilities themselves to ensure that their NPP primary systems can be effectively depressurised in all potential accident and transient situations, and that sufficient reactor core cooling can be provided at all times.

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FIGURES

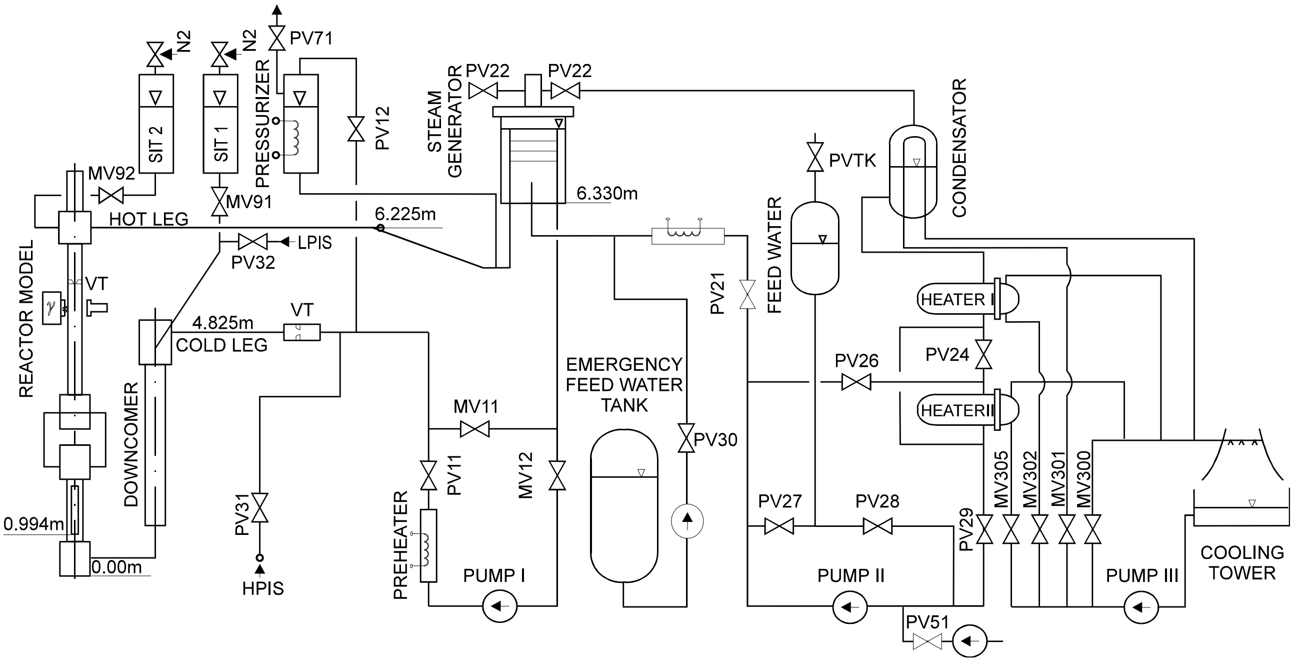


Figure 1. Flow diagram of PMK-2 test facility

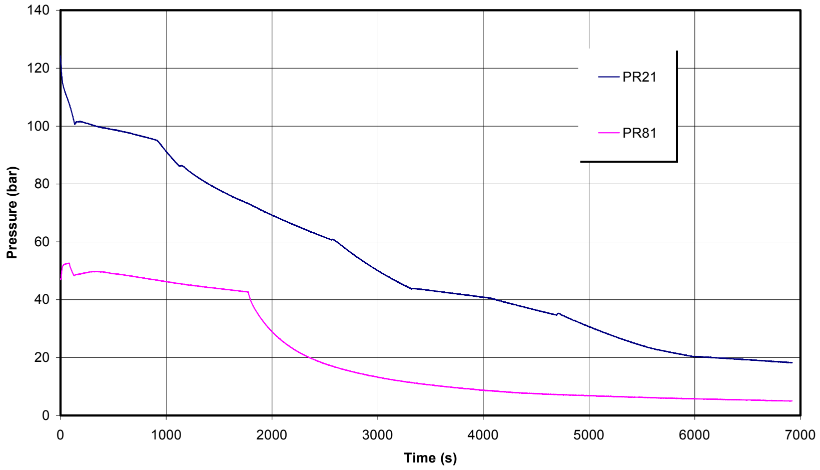


Figure 2. Primary (upper) and secondary pressures in PMK Test T1

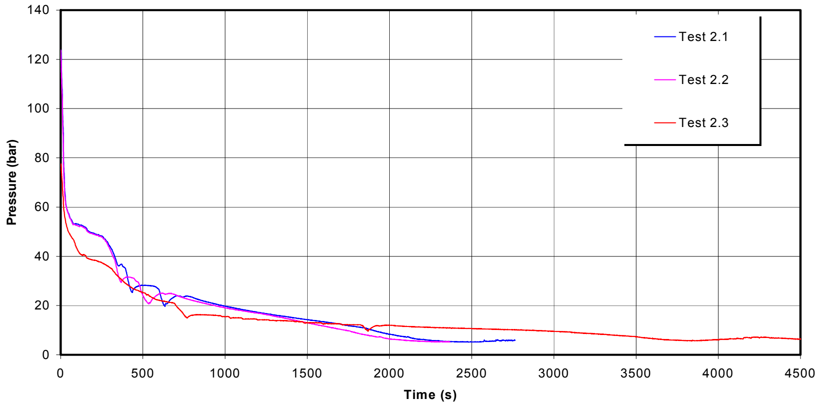


Figure 3. Primary pressures in PMK Tests T2 (T2.3 lowest in the beginning)

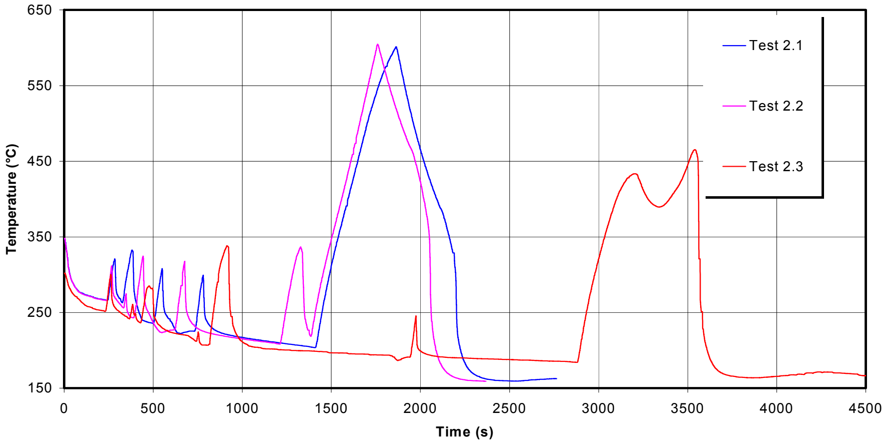


Figure 4. Cladding temperatures in PMK Tests T2 (first high peak in T2.2, last in T2.3)

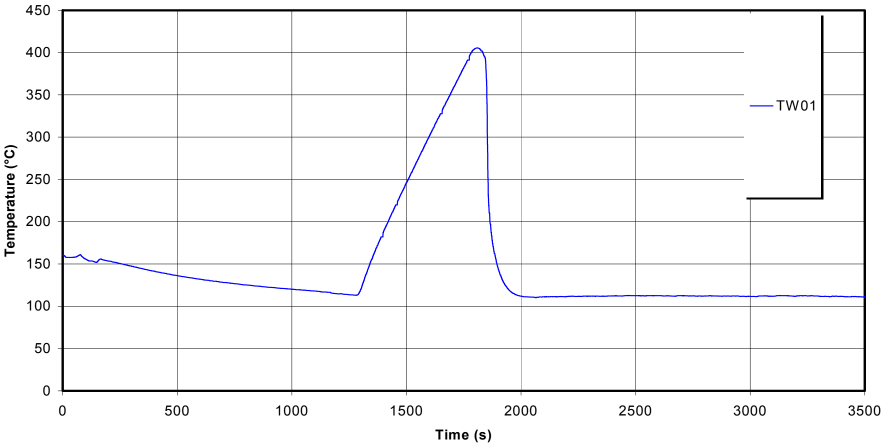


Figure 5 Cladding temperature in PMK Test T3.1 (no pre-heat-ups)

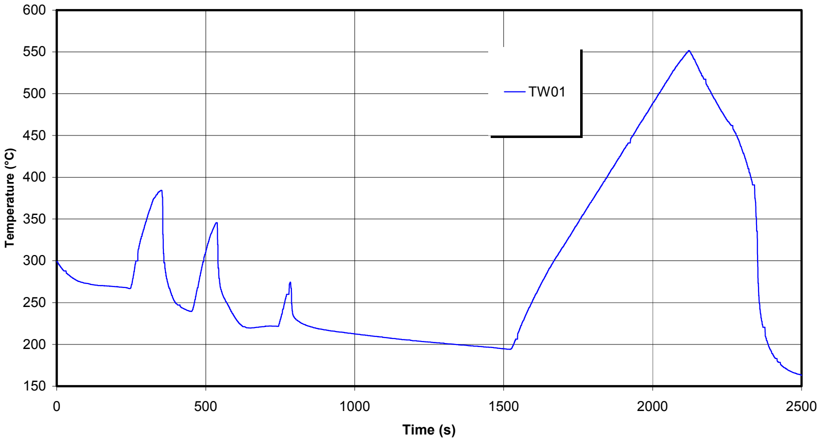
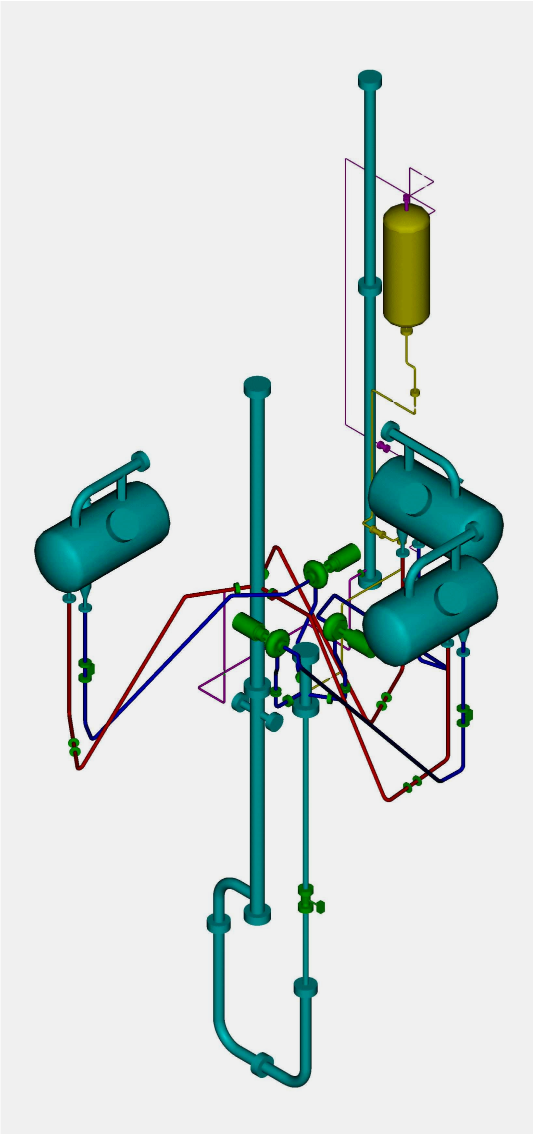


Figure 6. Cladding temperature in PMK Test T3.2 (peak quite late)



- models Loviisa VVER-440 NPP
- scaling 1:305
- full height
- max. pressure: 80 bar
- 3 active loops
- 144 electrically heated rods
- max. 22 % of scaled power (1 MW)
- different horizontal SG models used

Figure 7. PACTEL test facility

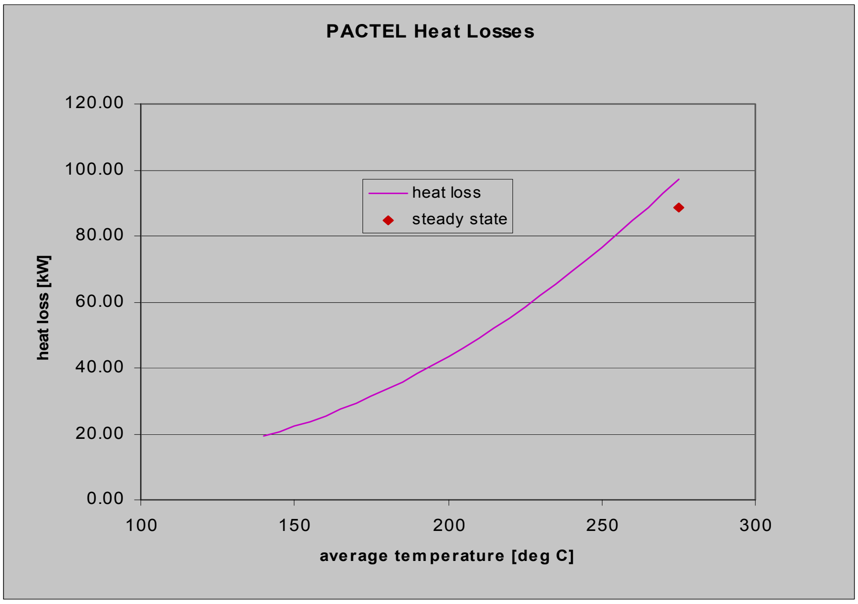


Figure 8. PACTEL heat losses

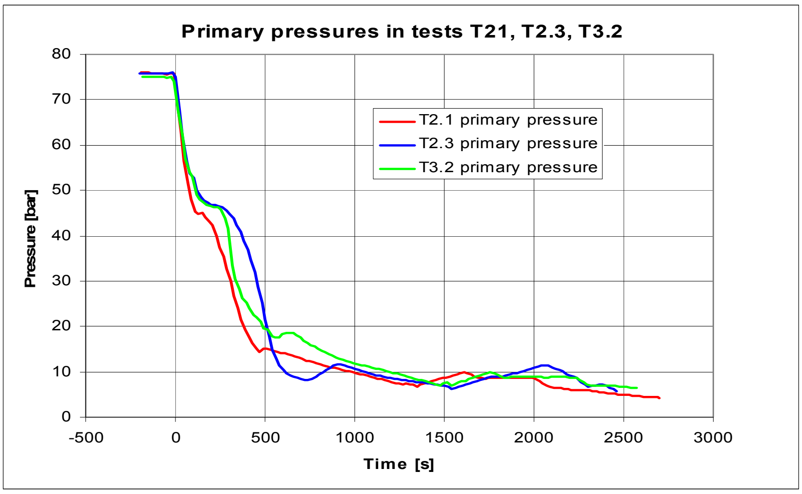


Figure 9. PACTEL primary pressures (at 700 s, T3.2 highest and T2.3 lowest)

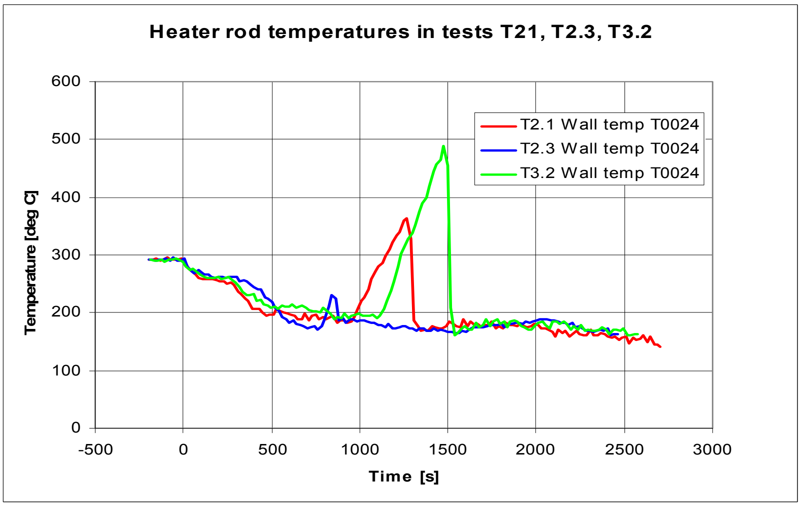


Figure 10. PACTEL heater-rod temperatures (highest peak in T3.2 and lowest in T2.3)

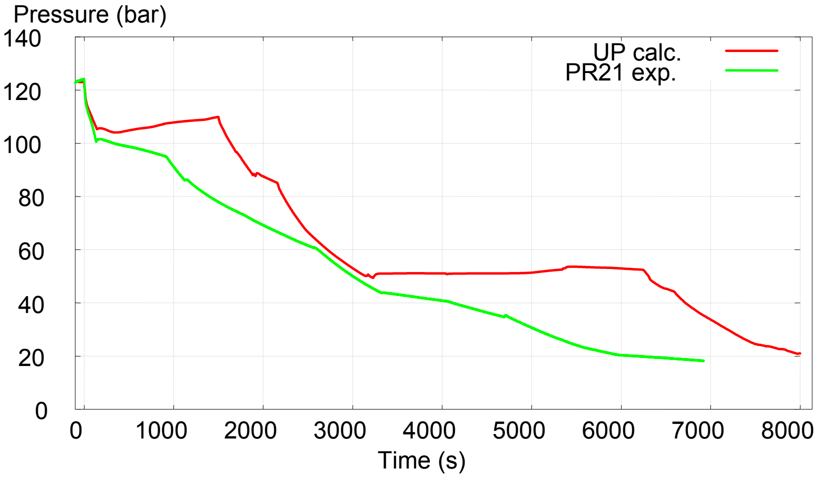


Figure 11. PMK Test 1: AEKI-calculated primary pressure by RELAP5 (higher curve)

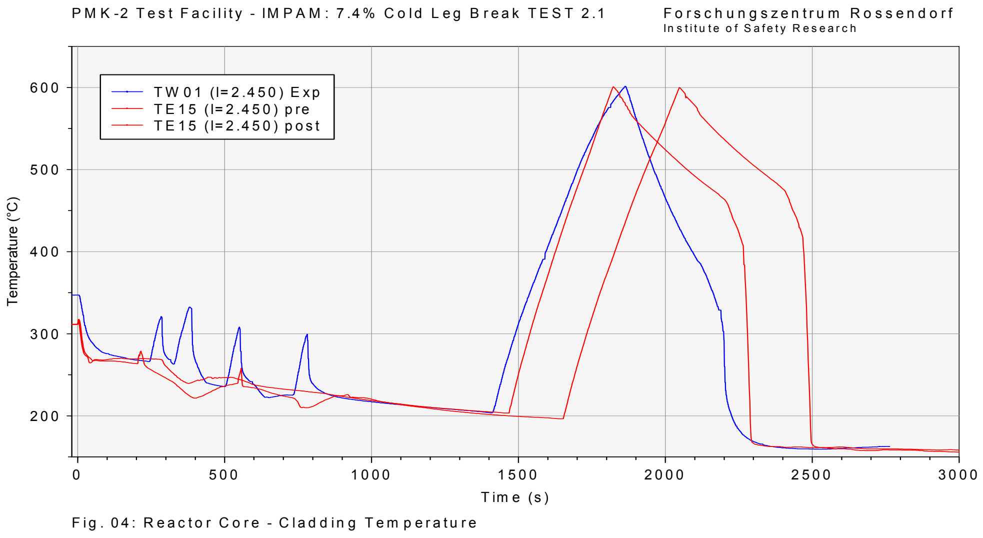


Figure 12. PMK Test 2.1 – FZR-calculated fuel-clad temperature by ATHLET (in pre-test analysis heat-up starts later than in the test)

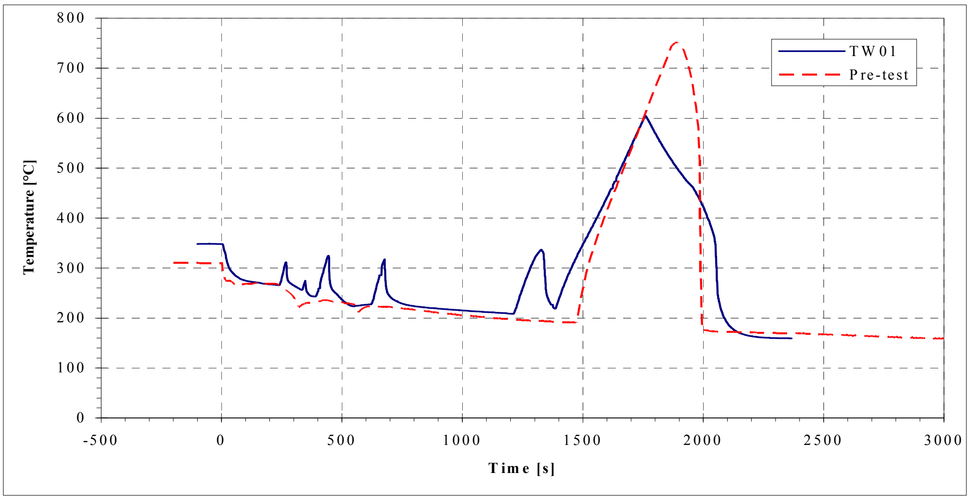


Figure 13. PMK Test 2.2 – Clad temperature by ATHLET (higher peak than in test)

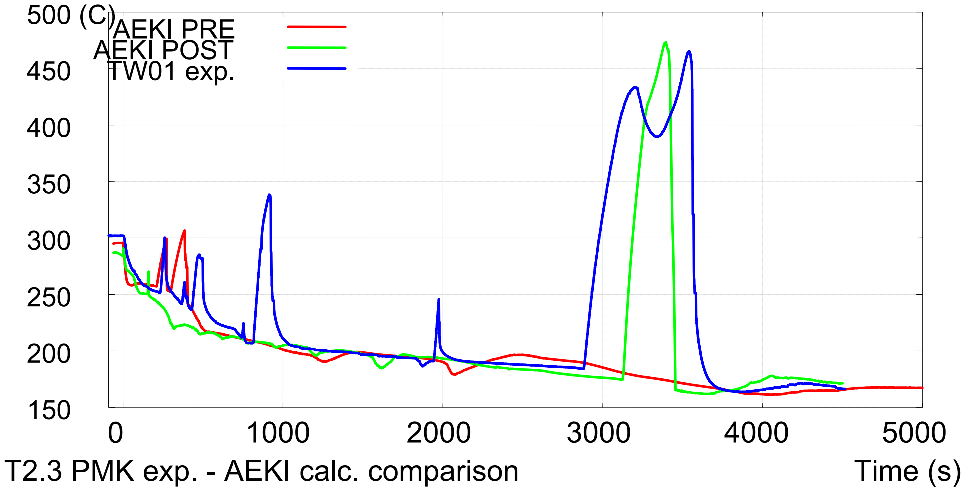


Figure 14. PMK Test 2.3 – Clad temperature by RELAP5 (post-test: one high peak with good timing; pre-test: no core overheating)

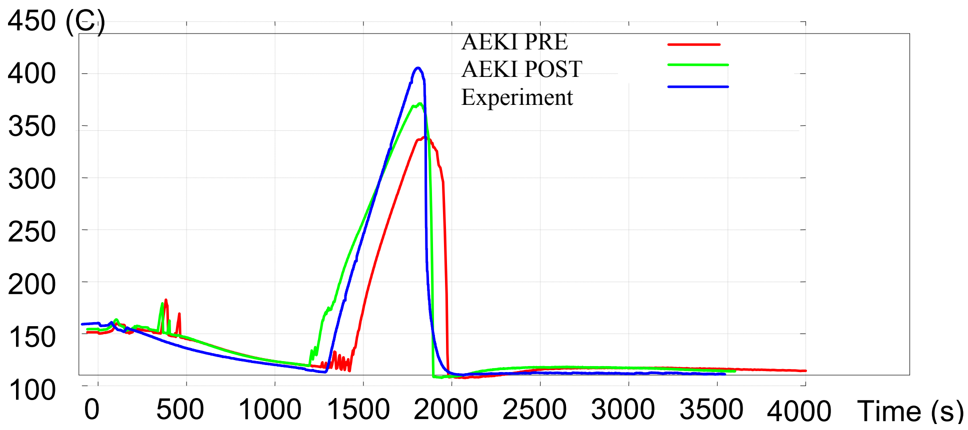


Figure 15. PMK Test 3.1 – AEKI-calculated fuel-clad temperature by RELAP5 (peak highest in the test; pre-test calculation lowest)

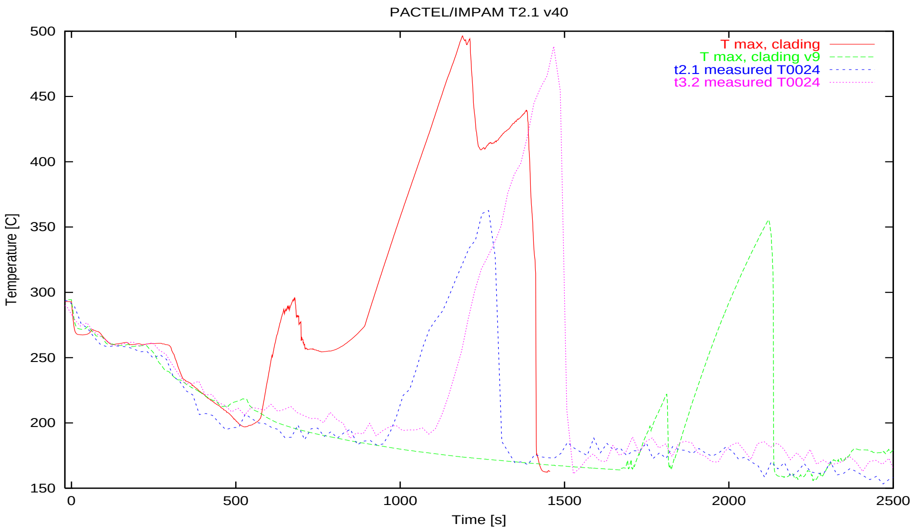


Figure 16. PACTEL Test 2.1 – Clad temperatures by APROS, showing high sensitivity to input data (two measured curves in the middle)

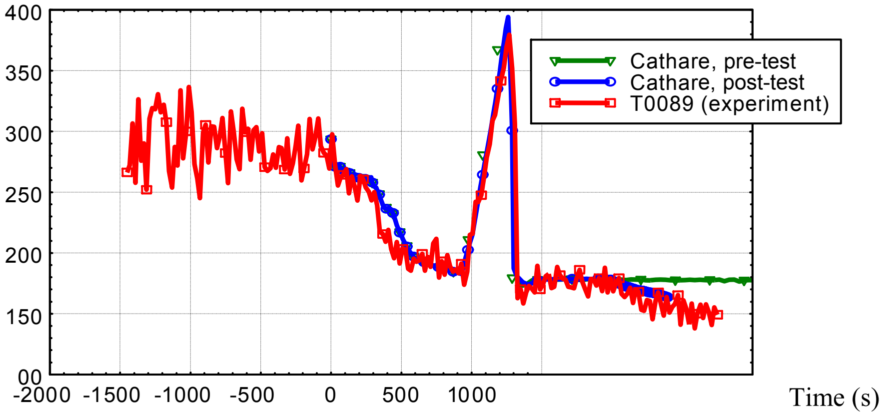


Figure 17. PACTEL Test 2.1 – IRSN-calculated clad temperature by CATHARE (very good predictions, especially post-test)

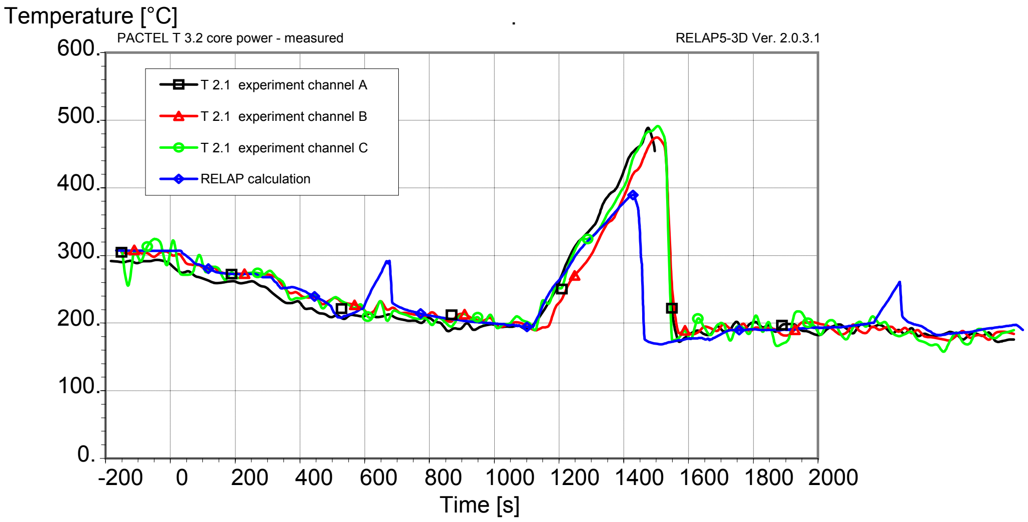


Figure 18. PACTEL Test 3.2 – IVS-calculated clad temperature by RELAP5-3D (calculation shows a lower peak than the experiment and an early peak at about 600 s)

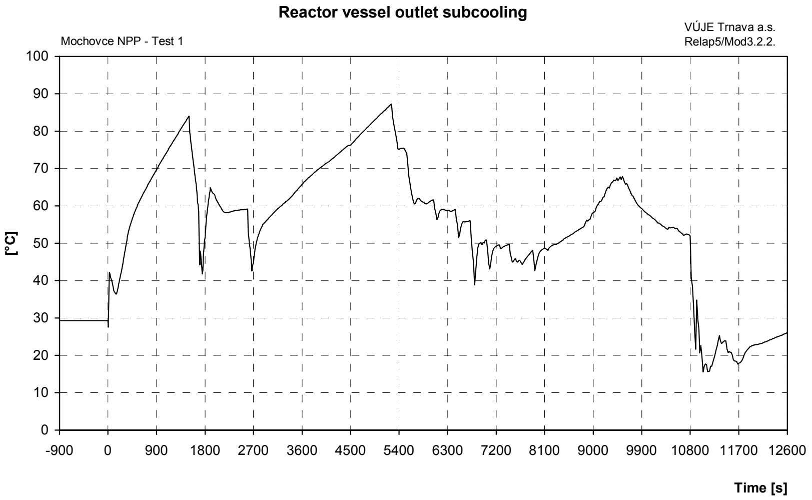


Figure 19. Mochovce transient analysis corresponding to Test T1: Reactor vessel outlet sub-cooling (compare with Figure 21)

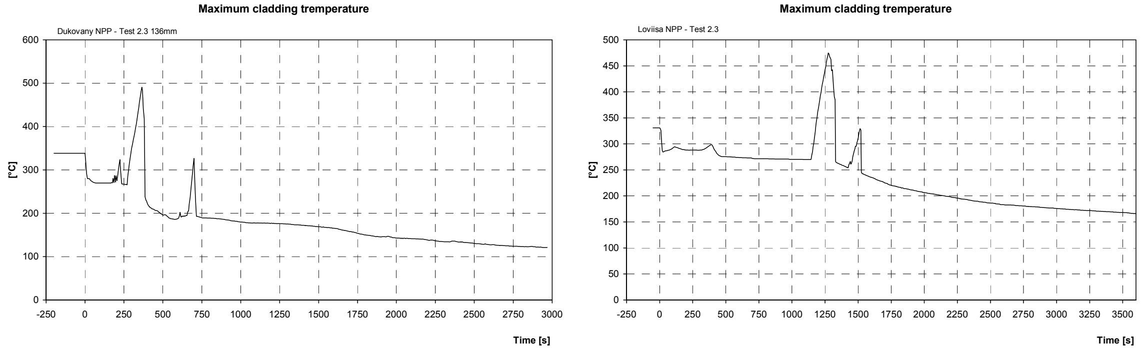


Figure 20. Dukovany (left) and Loviisa (right) transient analyses corresponding to Test T2.3: Maximum fuel-clad temperatures. For Dukovany, the temperature peaks are at about 300 and 700 s, for Loviisa at about 1250 and 1500 s

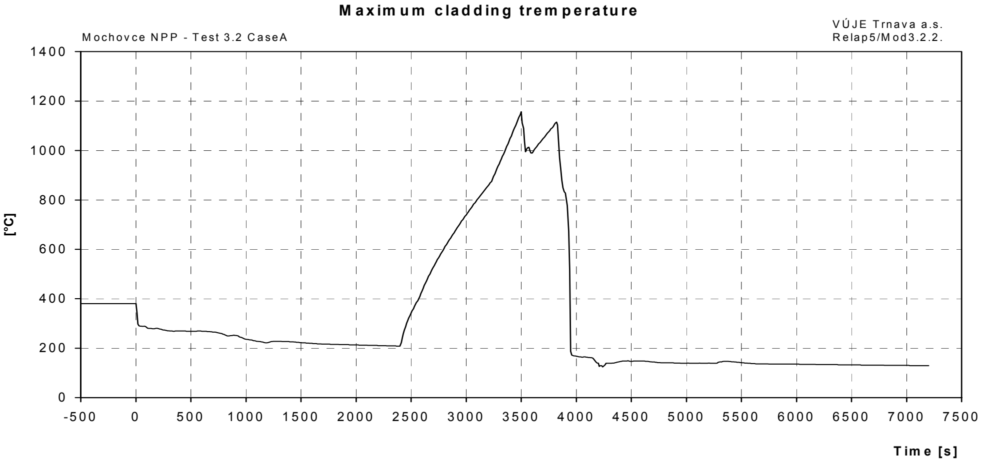


Figure 21. Mochovce transient analysis corresponding to Test T3.2: maximum fuel-clad temperature (Case A)

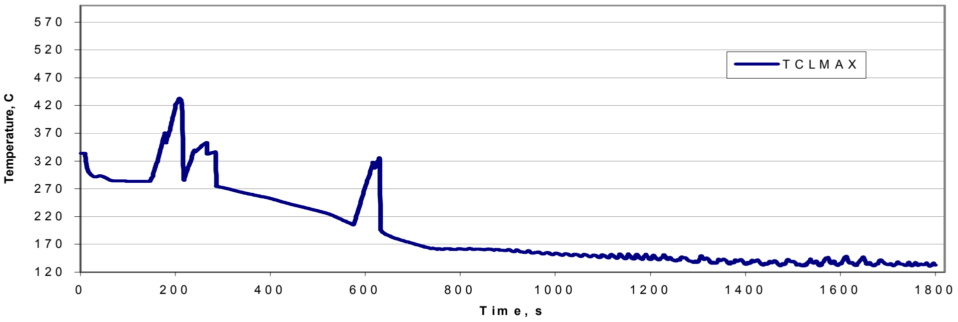


Figure 22. Kozloduy V1000 transient analysis corresponding to Test T2.1 (D 163 mm break, no operator actions): maximum fuel-clad temperature

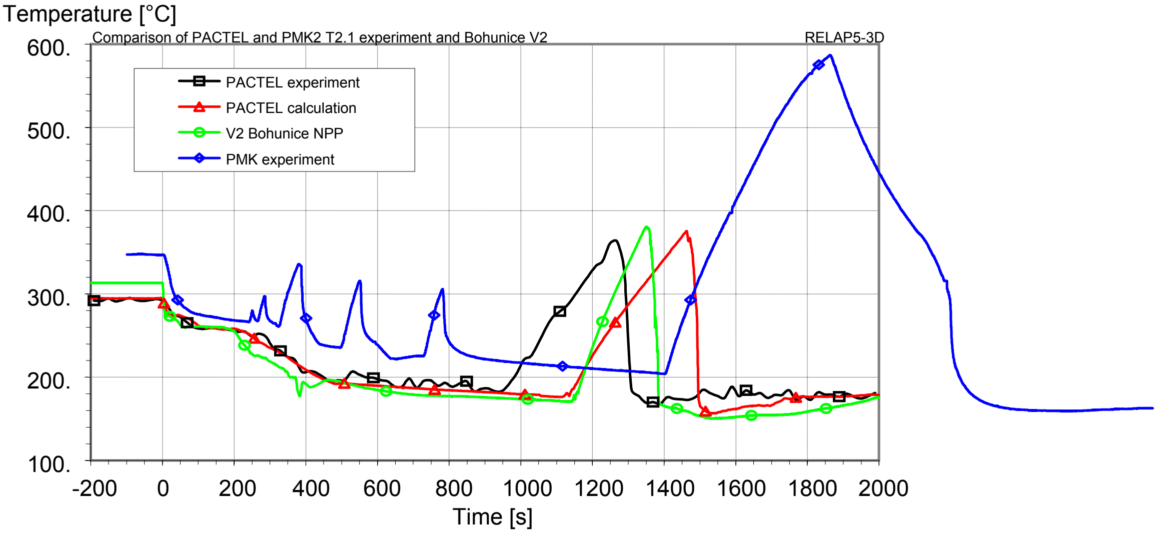


Figure 23. Comparison of maximum fuel-clad temperatures in Bohunice NPP, PACTEL Test T2.1 calculations, and test results of both PACTEL and PMK. PMK test results show a higher PCT than other results. The heat-up occurs first in PACTEL, then almost at the same time in the PACTEL and Bohunice calculations, and last in PMK