SMALL BREAK LOCA ANALYSIS OF MOCHOVCE NPP VVER-440/213 WITH OPERATOR ACTION

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ABSTRACT

The results of small break LOCA analyses with equivalent diameter 40 and 80 mm are presented in this report. The analyses were performed with the code RELAP5/Mod3.2.2β and a 6-loop design model for Mochovce NPP was used. The aim of performed analyses was to evaluate the operator action under the small break LOCA conditions and predefined emergency core cooling system (ECCS) configuration, when the operator action leads to ensuring the core cooling. Success of operator action was evaluated following the behaviour of core outlet coolant temperature and cladding temperature that was reached during the accident.

1 INTRODUCTION

To assure required safety level for NPP units it is necessary to make sure that all safety functions (SF) are functioning in the whole range of expected operational modes, which are expected or may occur within the lifetime of the unit. In standard classification of the unit safety features, SFs relate to the first, second and third level of the defence in depth strategy.

- First level of the defence in depth (normal operation) – limits and conditions of safe operation shall be maintained;
- Second level of the defence in depth (abnormal operation) – abnormal operation shall not evolve into an accident but the unit is brought to a stable conditions;
- Third level of the defence in depth (postulated accident) – coping with the accident and limiting its consequences to an acceptable level.

The safety analyses are one of the main tools of NPP safety assessment. Their role is to show the safety requests fulfilment for large scope of initiating events and operating states. For deterministic assessment within the range of postulated accidents, the safety criteria for deterministic assessment have to be fulfilled. For probabilistic assessment, core damage frequency is determined and it indicates the success or failure of safety systems, which functioning is needed to ensure individual safety functions.

The aim of analyses presented in this report was to evaluate the safety function that prevents the core damage under LOCA conditions for defined scenarios, as well as the operator action, which leads to ensuring of core cooling.

2 RELAL5 MODEL OF MOCHOVCE NPP

For evaluation of the effective changes, a 6-loop design model for Mochovce NPP has been developed for RELAP5/Mod3.2.2β. The 6-loop model describes the primary and secondary loops in detail, as well as all safety-important systems and most of control systems. The nodding scheme reflects both the general needs of thermo-hydraulic simulation (dimensions, elevations, volumes, areas) and the extent of safety analysis (simulation of large scope of scenarios).

Each of the six modelled primary loops has the same nodding except the PRZ component, the ECCS injection and make up system. ECCS consists of 4 HAs, 3 HPI pumps and 3 LPI pumps. In this model 2 HAs are connected to the downcomer and 2 HAs to the upper plenum. 3 HPI pumps are connected to the to the cold leg of loop 2, 3 and 5. 2 LPI pumps are connected to the HA surge lines and 1 LPI pump is connected to the cold leg as well as hot leg of loop 4.

Hydroaccumulators

- Volume of HA 70 m^3
- Water volume of HA 40 m^3
- Water temperature in HA 75 °C
- Initial pressure of HA 5.89 MPa
- H_3BO_3 concentration 12 g/kg

HPI system:

- Water temperature 60 °C
- H_3BO_3 concentration 40 g/kg
- HPI pump delay 10.0 s between start-up signal and beginning of water delivery

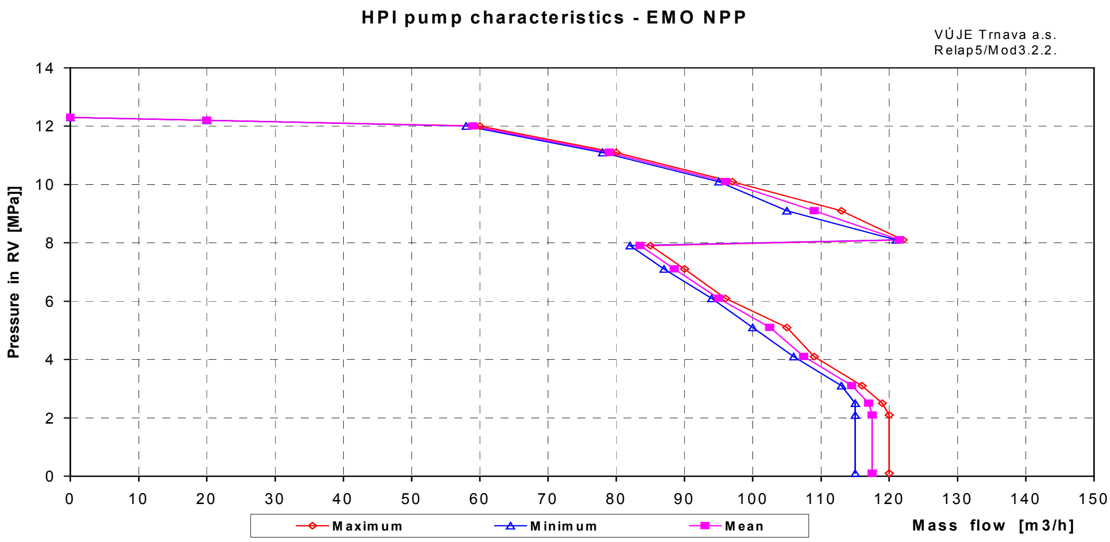
In case of LOOP, the total delay between LOOP and beginning of water delivery is 13.5 (DG start-up) + 0.0 (ASSS) + 10.0 = 23.5 s.

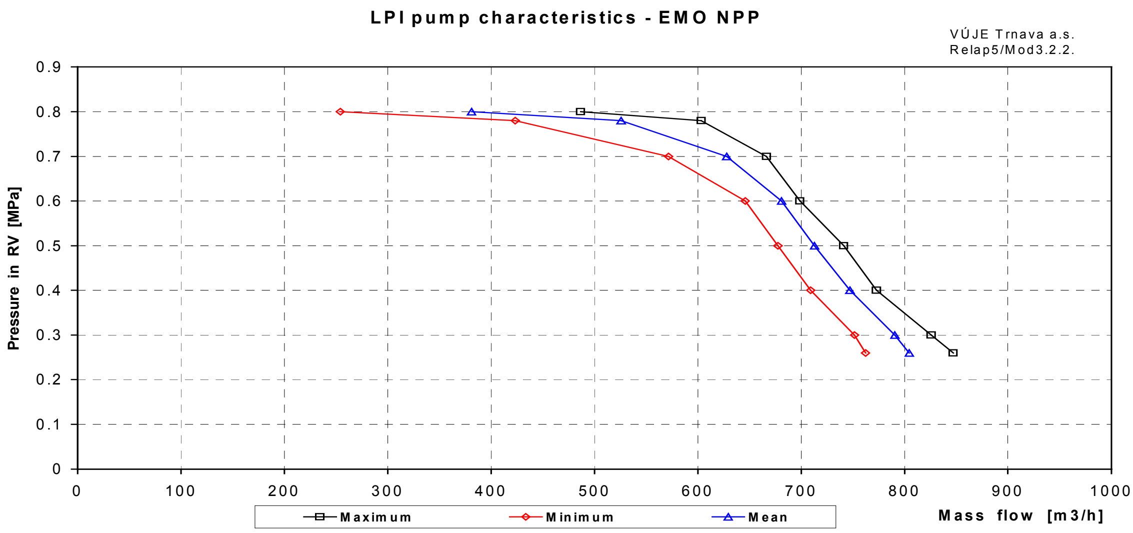
LPI system:

- Water temperature 60 °C
- H_3BO_3 concentration 12 g/kg
- LPI pump delay 10.0 s between start-up signal and beginning of water delivery

In case of LOOP, the total delay between LOOP and beginning of water delivery is 13.5 (DG start-up) + 10.0 (ASSS) + 10.0 = 33.5 s.

The HPI and LPI pump characteristics were obtained from operational measurement at Mochovce NPP. The maximum and minimum characteristics were obtained from this measurement and the mean characteristic was calculated as an arithmetical average.





3 DESCRITION OF SELECTED ANALYSES

The safety analyses of LOCA included in SAR are performed from the point of view of core cooling. The aim of these analyses is to show that the relevant acceptance criteria are met and the internationally acceptable level of nuclear safety and operational reliability is ensured. The conservatism of such analyses is ensured with selection of initial and boundary conditions, application of single failure and LOOP and other assumptions that are defined in the safety analyses methodology. The operator action is usually not assumed.

The aim of analyses presented in this report is to evaluate the operator action under LOCA conditions and to judge if this action leads to core cooling recover.

INITIAL AND BOUNDARY CONDITIONS

For analyses presented in this report, conservatism is applied for ECCS configuration only. The other initial and boundary conditions were assumed nominal, without uncertainties that could lead to conservatism of core cooling:

- nominal initial and boundary conditions,
- single failure and Loss Of Off-Site Power (LOOP) were not assumed,
- nominal value of scram and ESPAS signals setting,
- reactor power controller and turbine power controller were not assumed and operation of rest of non-safety systems was assumed in nominal mode.

CONFIGURATION OF ECCS AND MAKE-UP SYSTEM

The core cooling during the accident was supplied by 1 LPI pump and one/none HA only. The make-up operation is considered in nominal mode and after primary pressure decrease below 8.34 MPa make-up pumps are switched off. Additional operation of make-up pump is considered according to scenario in case when operator has to start up one make-up pump. Mass flow of one make-up pump equals 13.89 kg/s (50 t/hod) and mass of make-up tank, which can be injected to primary circuit, equals 100 m^3.

SCRAM SIGNALS:

- Primary pressure < 9.32 MPa,
- Primary pressure < 11,77 MPa and PRZ level < 3.26 m,
- Hermetic compartments pressure > 0.108 MPa.

ESFAS SIGNALS:

- Primary pressure < 8.34 MPa,
- Primary pressure < 10.77 MPa and PRZ level < 3.26 m,
- PRZ level < 2.76 m,
- Hermetic compartments pressure > 0.118 MPa.

OPERATOR ACTION

The operator action is necessary for recovering core cooling after initial event because HPIS is not assumed in any case. The basis of successful core cooling recovery is secondary circuit depressurisation, which leads to decrease of temperature and pressure of primary coolant and beginning of LP pumps injection. Parameter, which defines beginning of operator action, is core outlet coolant temperature equal to 370 °C. The delay between reaching of this temperature and the first operator action was assumed about 10 minutes because operator has to do some sequential steps leading to the action considered in the RELAP5 calculation. Some essential operator actions are listed below:

- secondary circuit depressurisation through all four BRU-Ks with the primary temperature decrease rate of 30 °C/hour or with maximum decrease rate (full opening of four BRU-A).
- 1 make-up pump start up,
- start-up of two main circulation pumps.

These steps of operator action were varied in the calculations together with break size and one HA or no HA injection.

CORE STATE ASSESSMENT AFTER INITIATING EVENT

The core state after initiating event is evaluated from point of view of NPP unit operation, if the core was not damaged (success) or was damaged (failure). In deterministic safety analyses, the acceptance criteria are defined for result of analyses evaluation and confirmation that an acceptable level of safety is ensured. For LOCA analyses, maximum cladding temperature (1200 °C) should be assumed as the crucial acceptance criterion from point of view of cladding (or fuel) damage.

In addition, data for number of leaked fuel rods evaluation are needed, because the cladding leakage can occur even if cladding temperature does not exceed 1200 °C but it is higher than ~ 750 °C in longer time interval. When the cladding temperature is higher than ~ 750 °C the partial degradation of Zr-Nb alloy mechanical properties can occur. This plastic degradation of cladding depends on core pressure and cladding temperature. The probability of partial degradation grows with cladding temperature increase and core pressure decrease, because the pressure difference between core and fuel-cladding gap increases [L3].

From the point of view of symptom-oriented emergency operating procedures, the core outlet coolant temperature serves as core damage criterion. If this temperature exceeds 550 °C the core damage is predicted. On the other hand, the plastic degradation of cladding can occur even if core outlet temperature is less than 550 °C but the cladding temperature is higher than 750 °C.

Therefore, following parameters were evaluated for the core state assessment:

- cladding temperature - higher than 1200 °C,
- time when cladding temperature is higher than 750 °C,
- core coolant level,
- core outlet coolant temperature - higher than 550 °C.

The core state after initiating event was evaluated using three levels:

I. level – NO core damage

Maximum cladding temperature does not exceed 1200 °C, time, when the cladding temperature is higher than 750 °C is shorter than ~ 300 s, core coolant level does not drop at 0.0 m and core outlet temperature is lower than 550 °C.

II. level – NO core damage but the probability of plastic degradation of cladding is high

Maximum cladding temperature does not exceed 1200 °C, time, when the cladding temperature is higher than 750 °C is longer than ~ 300 s, core coolant level drops at 0.0 m and core outlet temperature is lower than 550 °C.

III. level – core damage

Maximum cladding temperature exceeds 1200 °C and core outlet temperature is higher than 550 °C.

SPECIFICATION OF ANALYSED CASES

The 80 mm and 40 mm LOCAs in cold leg of the loop 1 (where PRZ is connected) were analysed. 8 analysed cases differed from each other in break sizes, HA functioning and make-up system operation. The all analysed cases are listed in the table below.

Table 1: Analysed cases

Case identification	**H0-x1**	**H0-x3**	**H1-x1**	**H1-x3**	**I0-x1**	**I0-x3**	**I1-x1**	**I1-x3**
Break equivalent diameter [mm]	80				40			
Number of HPI pumps	0	0	0	0	0	0	0	0
Number of HAs	0	0	1	1	0	0	1	1
Number of LPI pumps	1	1	1	1	1	1	1	1
Make-up system start up after t_{core} > 370 °C	No	Yes	No	Yes	No	Yes	No	Yes

4 RESULTS OF ANALYSES

Only 2 of all 8 analysed cases are described here in detail – H0-x1 and H1-x1. In these two cases, LOCA 80 mm is assumed as initiating event and make-up system operation as a result of operator action is not taken into account. None and one HA are available in the case H0-x1 or H1-x1, respectively. The results of the rest of analysed cases are summarized in the final evaluation only.

<u>Case H0-x1 (ϕ80 mm, 0 HA)</u>

Only 1 LPI pump is available for core cooling during the accident. The HPI pump, HA either make-up pumps are not assumed to supply water into primary circuit.

- The initial phase is characterised by depressurisation of primary circuit, but reactor is tripped by signal "pressure in hermetical compartmemts > 0.108 MPa" at 7.0 s.
- Signal small break "primary pressure < 11.77 MPa and PRZ level < 3.26 m" appears at 18.0 s but HPI system functioning is not assumed.
- Signal "pressure in hermetical compartments > 0.118 MPa" and the all MCPs are tripped.
- Primary pressure furthermore decreases and at 89.0 s reaches value of 5.89 MPa but HA functioning is not assumed. Primary pressure drop stops for first time at 250.0s when the water level in reactor vessel drops below the bottom rim of RV outlet nozzles and water density in hot leg seals rapidly decreases. Primary pressure equals approximately 4.8 MPa till 600 s. At 650 s, the water level in reactor vessel drops below the bottom rim of RV inlet nozzles, water density in break rapidly decreases and consecutive PC depressurisation continues. On the other hand, PC depressurisation is not sufficient to initiate LPI system before the core heat up.
- Maximum of break flow (479 kg/s) is reached in the beginning of accident at 10 s. Between 250 and 600 s break flow is equal to ~ 120 kg/s. After drop of water density at the break, coolant discharge decreases by about 50 % and goes down till the end of analyses. Due to absence of ECCS injection, the break is not supplied and reactor vessel mass inventory equals 24.5 ton on the end of calculation what represents 33 % of nominal mass inventory.
- Due to absence of ECCS injection, total RV level decreases and the core is quite uncovered at 1600 s (27 min).
- Core outlet temperature reaches 370 °C at 22.2 min and operator starts to perform sequential steps leading to core cooling recovery. Water injection from HA, HPI and make-up system is not successful (is not considered) and core outlet coolant temperature rises and at 27.1 min temperature reaches 550 °C. The first operator action was realised 32.2 min (11 min after 370 °C was reached) and operator starts to depressurise secondary circuit with maximum rate by opening of all four BRU-K. The aim of his action is to decrease primary pressure below value that allows LPI pump function.

- At time 27.1 min, when the core outlet coolant temperature equals 550 °C, maximum cladding temperature equals 923 °C and coolant level in the core is zero. The increase of cladding temperature is very sharp (~ 2 °C/s) and operator cannot perform effective steps because at time of the first operator action the cladding temperature is higher than 1200 °C (for all modelled heat structures).
- The calculation was terminated at 2127 s (35.4 min) because RELAP5 is not intended for calculation under the core melting conditions. At the end of calculation, maximum cladding temperature equals 1912 °C and core outlet coolant temperature equals ~ 900 °C. The secondary circuit was depressurised by operator to 1.45 MPa and primary pressure equals 0.87 MPa. The results of LOCA 80 mm analysis, where only 1 LPI pump is available for core cooling, indicate that operator action does not lead to LPI pump function. Assuming that no HPI pumps, HAs neither make-up pumps are able to supply water into primary circuit, core damage occurs.

<u>Case H1-x1 (ϕ80 mm, 1 HA)</u>

Only 1 HA and 1 LPI pump is available for core cooling during the accident. No HPI pump neither make-up pumps are assumed to supply water into primary circuit.

- The accident behaviour is the same as in case H0-x1 till the time when the primary pressure drops to 5.89 MPa. In this case, HA functioning is assumed and it starts to deliver water into the reactor. It causes that coolant level in the core during HA water delivery is kept between 1.6 and 2.0 m and primary pressure slightly decreases. HA is empty at 1440 s (24.0 min) and the primary pressure equals 2.46 MPa. After HA emptying, no coolant is injected into the primary circuit and it leads to a decrease of coolant level in core since 2700 s (45.0 min). Thereafter, core outlet coolant temperature starts to increase from 3000 s (50.0 min).
- Core outlet temperature reaches 370 °C at 58.2 min and operator starts to perform sequential steps leading to core cooling recovery. The first operator action was realised 67.2 min (9 min after 370 °C) and operator starts to depressurise secondary circuit with the rate of 30 °C/hour using all four BRU-K.
- Secondary circuit depressurisation is not effective immediately, because secondary pressure at the beginning of operator action equals ~ 4,7 MPa, but primary pressure equals 0,89 MPa. At 70.1 min, the primary pressure drops to 0.82 MPa and LPI pump connected to the loop 4 starts to injected water to the primary circuit. Although the water delivery is not continuous in the first stage, it is satisfactory to improve the core-cooling conditions. The increase in core outlet coolant temperature and cladding temperature is ceased and the maximum values are reached between 70.5 and 70.8 min (606 for core outlet coolant temperature and 1055 for cladding temperature). Similarly, the coolant level in the core starts to increase. From 77.7 min primary pressure is lower than 0.82 MPa and core cooling is ensured by LPI pump. From 74.4 min, secondary circuit is

depressurised with maximum rate by opening of all four BRU-K, because the core outlet temperature reaches 550 °C.

- At the end of the calculation (7200 s), core cooling is ensured by LPI pump operation, maximum cladding temperature and core outlet cooling temperature are lower than 130 °C, primary pressure equals to 0.8 MPa and secondary system is depressurised to atmospheric pressure. The result is that 2 hours after the initiating event core coolability is ensured.

Table 2: Significant events

Event	Case H0-x1		Case H1-x1	
	Time [s]	Value	Time [s]	Value
Initiating event	0.0	-	0.0	-
SCRAM Signal „pressure in HZ > 0.108 MPa^{abs}“	7.0	-	7.0	-
Small break signal „primary pressure < 11.77 MPa and L_{KO} < 3.26 m“	18.0	-	18.0	-
Signal „pressure in HZ > 0.118 MPa^{abs}“ – MCP tripped	20.0	-	20.0	-
Primary pressure < 5.89 MPa	89.0	-	89.0	-
HA empty	-	-	1440.0	integ 36.1 t
$T_{core-coolant}$ at the core outlet > 370 °C	**1333.0**	**22.2 min.**	**3494.0**	**58.2 min.**
Max. cladding temperature ($T_{core-coolant}$ = 370 °C)	1333.0	645.0 °C	3494.0	712.0 °C
Coolant level in the core ($T_{core-coolant}$ = 370 °C)	1333.0	0.57 m	3494.0	0.88 m
Primary pressure ($T_{core-coolant}$ = 370 °C)	1333.0	2.79 MPa	3494.0	1.13 MPa
Minimum of coolant level in the core	1610.0	0.0 m	4185.0	0.0 m
The first secondary circuit depressurisation	-	-	4034.0	67.2 min.
Minimum of coolant level in the core	-	-	4185.0	0.0 m
Primary pressure < 0.82 MPa (LPI pump)	-	-	4206.0	70.1 min.
$T_{core-coolant}$ at the core outlet > 550 °C	**1627.0**	**27.1 min.**	**4227.0**	**70.4 min.**
Max. cladding temperature ($T_{core-coolant}$ = 550 °C)	1627.0	923 °C	4227.0	1055 °C
Coolant level in core ($T_{core-coolant}$ = 550 °C)	1627.0	0.0 m	4227.0	0.2 m
The first secondary circuit depressurisation	1990.0	33.2 min.	-	-.
Primary pressure < 0.82 MPa (LPI pump)	-	-	-	-
Maximum cladding temperature	**1824**	**>1200°C**	**4230.0**	**1056°C**
Max. cladding temperature < 200 °C	-	-	4760.0	79.3 min
End of calculation	2127.0	-	7200.0	-

5 RESULTS EVALUATION

Time when the core damage is predicted is reached only for level III. and is the same as the time when the maximum cladding temperature equals 1200 °C. Time when core outlet temperature exceeds 370 °C and 550 °C is included in the table as well, because these parameters define beginning of the operator action.

Table 3: Core state assessment

Variant	T_{c-c} > 370 °C	Maxim. cladding temper. > 750 °C	T_{c-c} > 550 °C	Maxim. cladding temper.	The first operator action	Core state level
H0-x1 (ϕ80, 0-HPI, 0-HA, 1-LPI, 0-make-up)	22.2 min	24.0 min	27.1 min	30.4 min > 1200 °C	33.2 min secondary circuit depressurisation	**III.**
H0-x3 (ϕ80, 0-HPI, 0-HA, 1-LPI, 1-make-up)	22.2 min	24.0 min	27.1 min	30.4 min > 1200 °C	33.2 min 1 make-up pump start up	**III.**
H1-x1 (ϕ80, 0-HPI, 1-HA, 1-LPI, 0-make-up)	58.2 min	59.4 min	70.4 min	70.5 min 1056 °C	67.2 min secondary circuit depressurisation	II.
H1-x3 (ϕ80, 0-HPI, 1-HA, 1-LPI, 1-make-up)	58.2 min	59.4 min	70.7 min	76.7 min 1086 °C	69.2 min 1 make-up pump start up	II.
I0-x1 (ϕ40, 0-HPI, 0-HA, 1-LPI, 0-make-up)	78.4 min	70.1 min	-	82.1 min > 1200 °C	does not come to it (secondary circuit depressurisation)	**III.**
I0-x3 (ϕ40, 0-HPI, 0-HA, 1-LPI, 1-make-up)	78.4 min	70.1 min	-	82.1 min > 1200 °C	does not come to it (1 make-up pump start up)	**III.**
I1-x1 (ϕ40, 0-HPI, 1-HA, 1-LPI, 0-make-up)	68.1 min	188.0 min	-	188.3 min 847 °C	77.1 min secondary circuit depressurisation	II.
I1-x3 (ϕ40, 0-HPI, 1-HA, 1-LPI, 1-make-up)	68.1 min	-	-	81.2 min 671 °C	79.1 min 1 make-up pump start up	I.

- In cases where 1 HA is available (H1-x1, H1-x3, I1-x1, I1-x3), core damage is not predicted. The operator action is effective from point of view of the core cooling.
  - In H1 cases (1 HA a LOCA ϕ80), HA is empty before the first operator action because primary pressure decrease is sharper than in I1 cases (1 HA a LOCA ϕ40). After HA emptying, core outlet temperature starts to increase but secondary circuit depressurisation and consequently, primary pressure drop below 0.82 MPa leads to LPI pump start up.
  - In I1 cases, depressurisation of SC and PC is needed to enable injection from 1 HA. After this happens, operator continues in depressurisation that leads to LPI pump start up.

- In cases where 1 HA is not available (H0-x1, H0-x3, I0-x1, I0-x3), core damage is predicted and the core state assessment is defined with level III. The operator action is not effective from the point of view of core cooling, or he fails to execute it. The reason is rapid increase in core outlet coolant temperature as well as in cladding temperature. In addition, operator cannot realise the first action sooner than 9 min after the core outlet coolant temperature reached 370 °C.

- In H0 cases, time interval between the point when the core coolant outlet temperature reaches 370 °C and the point when maximum cladding temperature equals 1200 °C is only 8.2 min.
- In I0 cases, time interval between the point when the core coolant outlet temperature reaches 370 °C and the point when maximum cladding temperature equals 1200 °C is only 3.7 min.

According to the results mentioned above, core outlet coolant temperature equal to 370 °C or 550 °C is not sufficient for operator to perform effective steps and to recover core cooling. In addition, time interval between the point when the core coolant outlet temperature reaches 550 °C and the point when maximum cladding temperature equals 1200 °C is only 3.3 min in H0 cases. In I0 cases, cladding temperature equals 1200 °C, but core outlet coolant temperature is below 550 °C.

- No substantial differences were found when 1 make-up pump starting was assumed as the first operator action instead of secondary circuit depressurisation. In cases where SC depressurisation was effective, then 1 make-up pump starting was effective too (H1-x1 and H1-x3; I1-x1 and I1-x3). On the other hand, if SC depressurisation was not effective, then 1 make-up pump starting was not effective either (H0-x1 and H0-x3; I0-x1 and I0-x3).
- The start-up of two main circulation pumps and their effect on the core cooling was verified (results of these calculations are not included in the table 3). The results showed that efficiency of two main circulation pumps start-up from the point of view of core cooling is disputable. Operator can put into operation MCP only when the previous steps do not lead to core cooling recovery.
  - In cases where 1 HA is available, operator action is effective and LPI pump operating ensures core cooling. There is no reason to start-up main circulation pumps.
  - In cases where 1 HA is not available, core damage is predicted before the first operator action and, likewise, there is no reason to start-up main circulation pumps.

5 CONCLUSION

The results of LOCA 80 and 40 mm analyses indicate that operator action in term of core cooling is effective in case where 1 HA and 1 LPI pump are available. After reaching core outlet coolant temperature of 370 °C, operator action leads to core cooling recovery and cladding temperature does not exceed 1200 °C. In the case where only 1 LPI pump is available and none HA and HPI pump is assumed, operator steps are not effective from the point of view of core cooling recovery and cladding temperature exceeds 1200 °C. Core outlet coolant temperature equal to 370 °C or 550 °C is too high as criterion for execution of effective steps leading to the core cooling recovery.

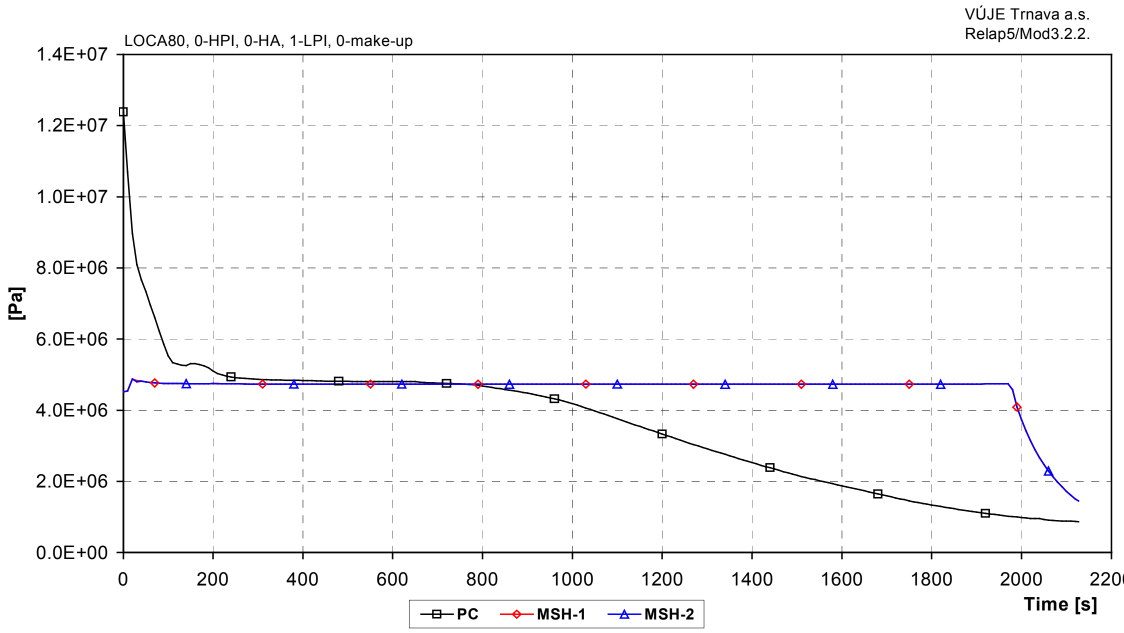


Fig. H0-x1-1 Primary pressure and main steam header pressure

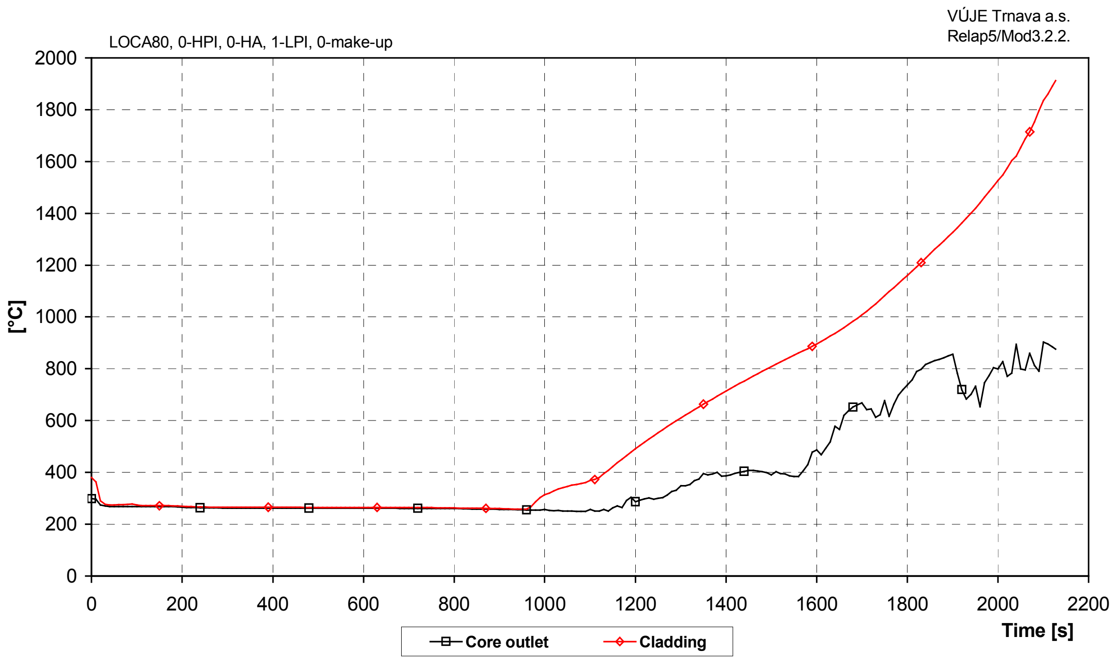


Fig. H0-x1-2 Core outlet coolant temperature and maximum cladding temperature

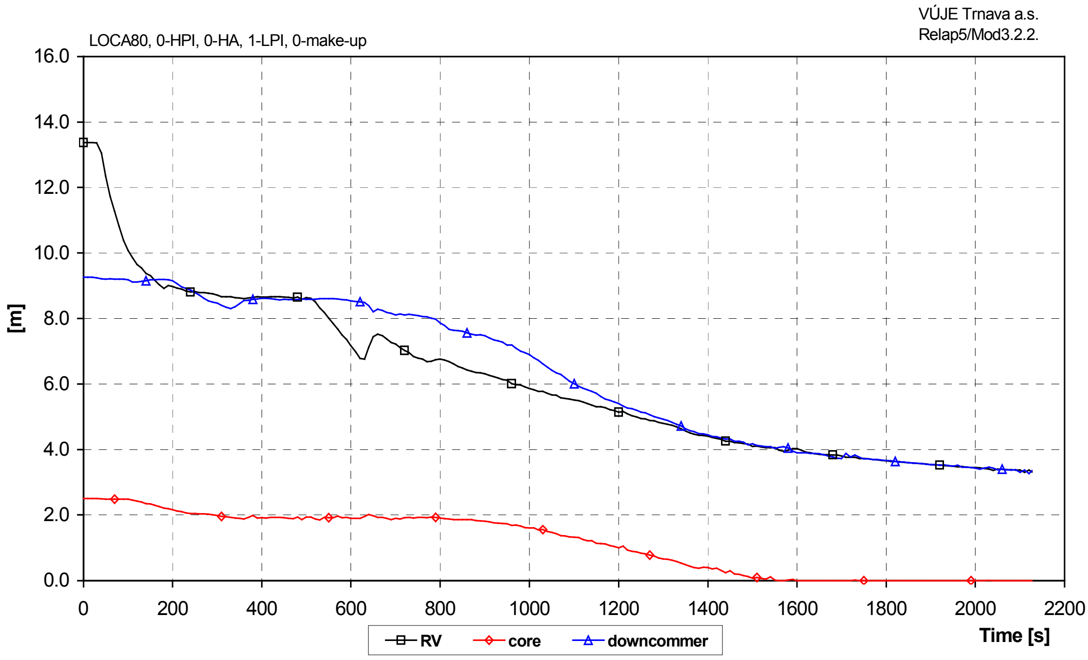


Fig. H0-x1-3 Water level in reactor vessel, core and downcommer

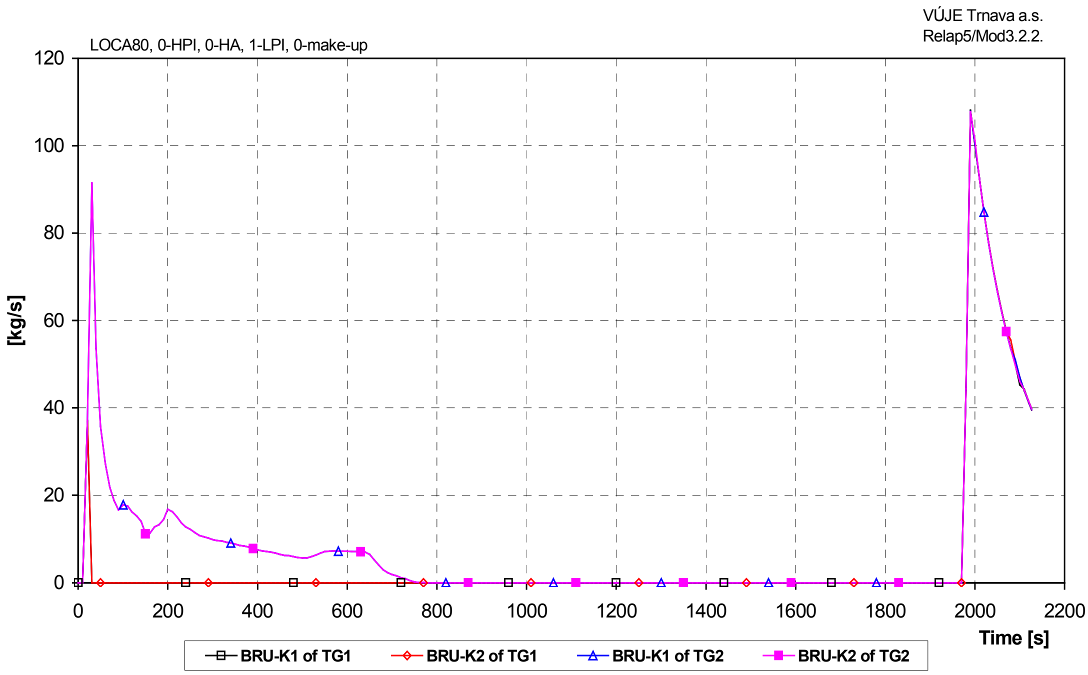


Fig. H0-x1-4 Steam flow through BRU-K

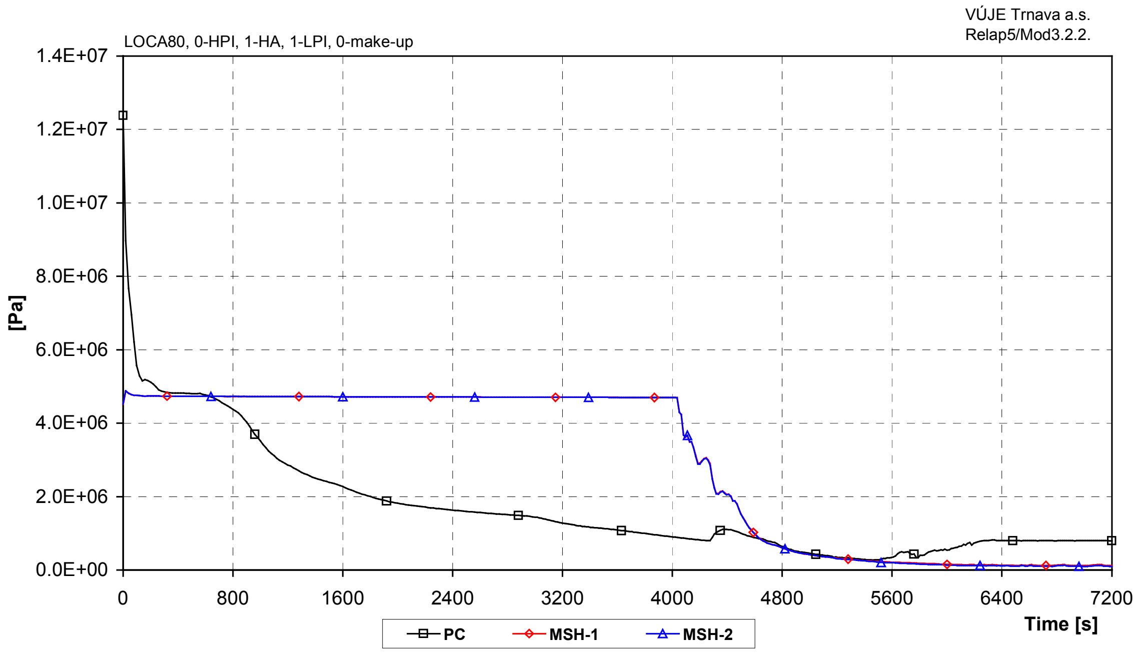


Fig. H1-x1-1 Primary pressure and main steam header pressure

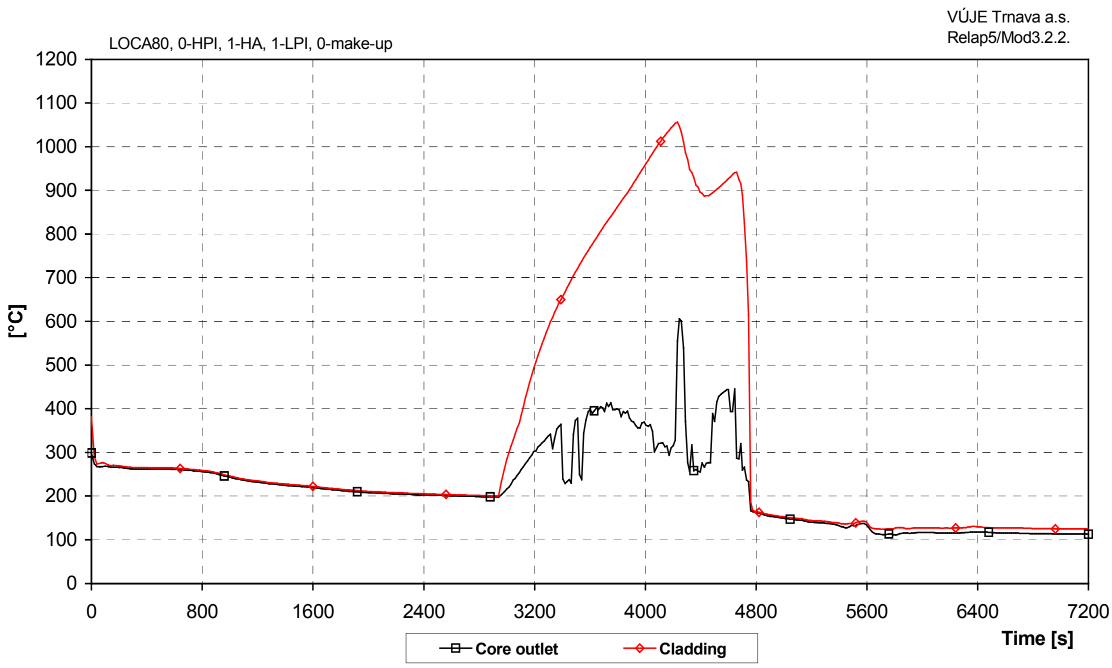


Fig. H1-x1-2 Core outlet coolant temperature and maximum cladding temperature

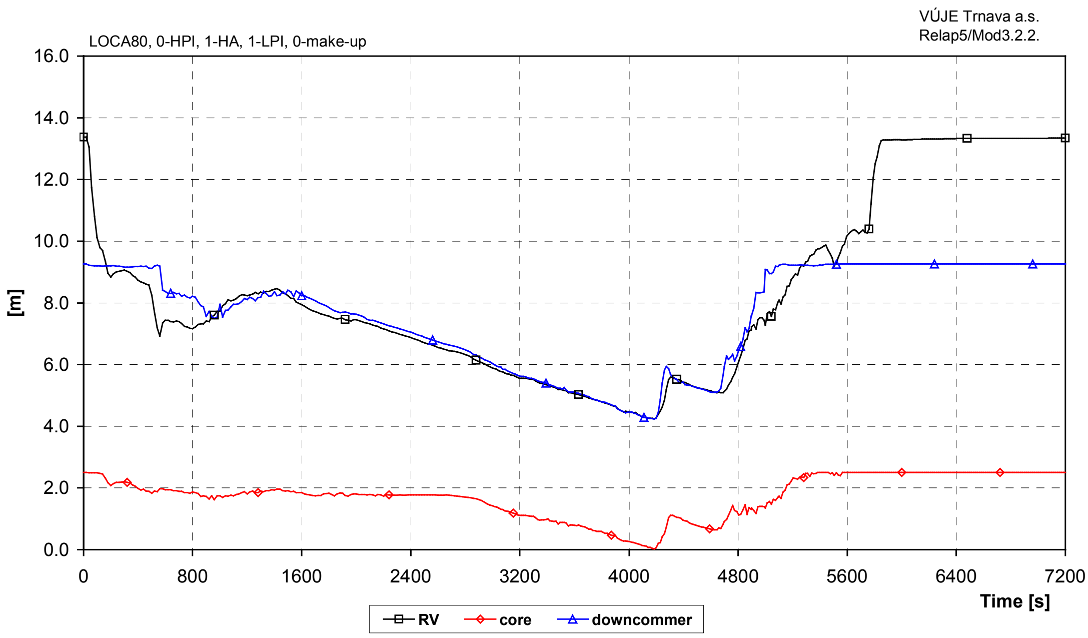


Fig. H1-x1-3 Water level in reactor vessel, core and downcommer

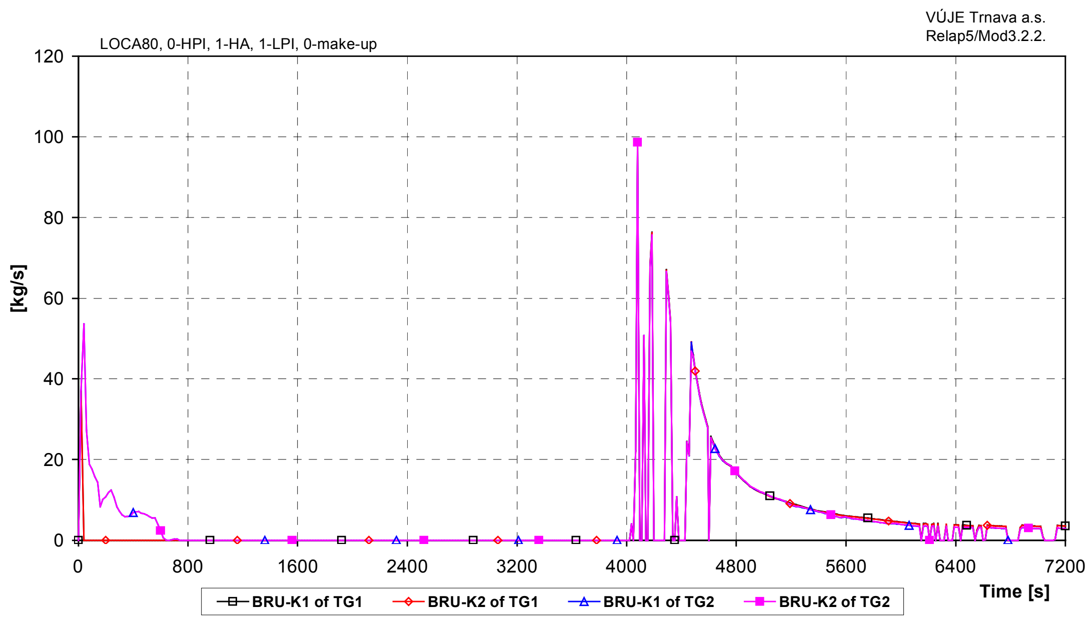


Fig. H1-x1-4 Steam flow through BRU-K

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