Fifth International Information Exchange Forum
Safety Analysis for NPPs of WWER and RBMK types
16-20 October 2000, Obninsk, Russian federation

Loss of off-site power transient in WWER-1000 reactors

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Background for the study

This paper presents some of the results obtained during the Basic Engineering Phase of the Modernization programme of Kozloduy NPP Units 5 and 6 for the measure, aimed at provision of the possibility to operate the emergency feed water system for at least 24 hours. The measure was included in the Programme due to the following reasons:

Violation of norm/standard: the WWER1000/320 design was developed before OPB-88/97 was put in force. One of the objectives of the Modernization programme is to bring the plant up to the current safety standards. Therefore measures shall be foreseen for management of beyond design basis accidents.

The results of PSA level 1 for Kozloduy 5&6 indicate that the loss of off-site power is one of the major contributors to the overall risk for core damage (41%).

The IAEA mission for evaluation of the Modernization programme in 1995 as well as the review of the programme, performed by RISKAUDIT, recommended the specification of measures aimed at ensuring of the capability of the emergency feed water system (TX) to be operated for at least 24 hours.

The solution of the problem includes 2 main parts:

- Study of the reliability of the emergency feed water system components;
- Study of the possibility to use the emergency feed water system to remove the decay heat for at least 24 hours. This includes first a cool-down of the plant to the parameters, when the residual heat removal system can be started and then, postulating a failure of the latter, decay heat removal using the emergency feed water system.

The study performed by ENPRO covered only the second part of the problem. Some of the results of this study are presented in this paper.

The calculations were performed using Relap5/3.2. The plant model was validated against plant data for a loss of off-site power transient at KNPP Unit 6.

Description of the transient

Operational experience shows that the event should be classified as an operational transient. Such an event occurred at Kozloduy NPP Unit 6 during 1992. Therefore the applicable acceptance criteria are those for operational transients.

Automatic actions

The loss of off-site power (LOOP) causes the closing of the turbine stop valves, tripping of the reactor coolant pumps, loss of the feed water supply to the steam generators and reactor trip. Due to the LOOP signal the first program for automatic sequential start of the safety systems (ASSS) is actuated. The loss of secondary heat removal leads to an increase of the primary and secondary pressure and opening of the steam dump to atmosphere facilities (BRU-A).

The first ASSS program starts both the high and medium pressure safety injection pumps at 20 s of transient, but none of them starts to supply concentrated boron solution to the primary circuit. This is so because for the injection of the high pressure pumps an operator action is needed to close their recirculation lines, while the head of the medium pressure pumps is lower that the primary circuit pressure. A little later, 55 s into the transient, the emergency feed water pumps are started too, but the valves on their delivery lines remain closed, being controlled by the SG levels and the pumps run in recirculation mode too.

The primary pressure stabilizes about its nominal value and is maintained by the operation of BRU-A until the 15-th minute of the transient. After that, due to the continuous decrease of the levels in the steam generators, the heat removal starts to deteriorate and the primary pressure – to increase. After the SG levels decrease below the setpoint values, the delivery side valves of the emergency feed water pumps open. Initially the first train of the system begins to inject to two of the steam generators, followed by the second and third trains of the system, each to two SGs. The injection to SGs 2 and 4 by the first train of the EFW system begins some 17-18 minutes after the initiating event. The injection to SGs 1 and 3, which are supplied by trains 2 and 3 of the system, begins between the 24-th and the 37-th minute, depending on the unit.

At the time when the EFW begins to inject cold water to the steam generators, the water levels there are rather low (below 1.3 m). Because of the rapid condensation after cold water injection and because of the lack of flow measurements and flow control to two of the steam generators (1 and 3), soon after the beginning of injection to these two SGs an isolation signal is generated (SG pressure below 5 MPa and pressure difference across the check valve less than –0.196 MPa). This leaves two steam generators without any feed water supply unless the operators reset the signal.

To summarize, the automatic safety features of the plant result in:

- Beginning of emergency feed water injection to all SGs and its termination to two of the SGs without a possibility to restore unless a set of operator actions are performed;
- No injection of concentrated boron solution to the primary circuit.

Therefore operator actions are mandatory in order to fulfil the requirements for safe shutdown of the plant, as specified in the current plant documents:

- Create a shutdown boron concentration in the primary circuit prior to initiation of organized cool-down;
- During the organized cool-down with a cool-down rate of 20°C/h, maintain the subcooling in the hot legs as close as possible to the value for normal operation (55°C).

Of course, in case of LOOP these requirements shall be fulfilled using only safety systems (with emergency power supply). Besides, according to the current regulations in the plant, the cool-down should be started within 30 minutes.

Evaluation of the immediate operator actions

The <u>possibilities for boron injection in case of LOOP</u> are limited to the high pressure boron injection system (3 high head pumps with a capacity of 6 t/h each) and the medium pressure boron injection pumps (with high capacity but relatively low head). The three high head pumps are not capable to inject enough boron in the required 30 minutes, even if the operators act very fast and start the injection immediately. The required shut-down value can be reached only if the primary circuit is depressurized sufficiently to permit the injection of the medium pressure pumps. In case of LOOP there are two possibilities for <u>primary circuit depressurization</u> – by opening of a pressurizer safety valve or by using the emergency gas evacuation system, both safety graded and operable from the main control room. The opening of a pressurizer safety valve will result in a rapid increase if the pressure in the relief tank, failure of the rupture disks and LOCA to the containment, which is not acceptable for an operational transient. Therefore the emergency gas evacuation system is the better solution. The calculations performed within the study show that this system is capable to depressurize the primary circuit sufficiently and ensure the prescribed boron concentration within the prescribed time. As the system is operated manually, the first attempt was to follow the procedures and open the lines when the subcooling increases to 70 K and close them when it drops to 30 K.

This attempt was not successful, therefore it was assumed that the operators open the lines at 40 K and close them at 20 K, giving a sufficient margin to the plant protection signal (containment isolation) at subcooling below 10 K.

To illustrate the effect of different operator actions, an example is given of the transient progression during the first hour for Unit 6 and Kozloduy NPP. Three cases with the same operator actions, applied at different time and/or different criteria were considered:

Case	Operator actions
1	At 15 min: close recirculation lines of the TQ4 pumps (start boron injection) start reducing of the primary pressure by opening/closing of the YR line when the subcooling in the hot legs is respectively ≥70°C and ≤30°C (try to maintain approximately 55°C)
2	At 15 min: close recirculation lines of the TQ4 pumps start reducing of the primary pressure by opening/closing of the YR line when the subcooling in the hot legs is respectively ≥40°C and ≤20°C (prevent containment isolation)
3	At 15 min: close recirculation lines of the TQ4 pumps At 30 min: start reducing of the primary pressure by opening/closing of the YR line when the subcooling in the hot legs is respectively ≥40°C and ≤20°C (see case 2)

The calculations show that, assuming at least 15 min delay for operator actions, it is not possible to fulfil the requirements defined in the plant regulations in 30 minutes. Therefore longer time was accepted.

The operator actions are considered to be successful if within 60 minutes after LOOP:

1. Boron concentration in the primary circuit higher than 7 g/l (specific for the selected initial and boundary conditions);
2. The pressurizer is not filled with liquid water (there was no two-phase or liquid flow in the YR line). This requirement is due to the lack of qualification of the line for two-phase and liquid flow.

Case 1 does not fulfil the criterion for reaching of the shutdown boron concentration because of the attempt to maintain a subcooling margin, which is typical for normal operation. Both cases 2 and 3 fulfil the two criteria listed above in 45 min. Case 3 results in a subcooling margin, which is closer to the prescribed value of 55 K.

Cool-down of the plant

The calculations performed for the initial phase of the transient show that in all cases it is necessary eliminate the signals for isolation of the steam generators in order to start an organized cool-down process. The calculations show that at least two of the steam generators will be isolated after 45 min of the transient.

The systems and equipment available for the process in the event of LOOP are the emergency feed water system and the steam dump to the atmosphere facilities (BRU-A). The BRU-A stations can be used in cool-down mode by selecting a cool-down velocity of 20 K/h or 60 K/h (the second is only for primary to secondary leaks). The parameter that is used to control the cool-down rate is the pressure in the respective steam generator.

Because of LOOP, the cold spray to the pressurizer is not available and the operators can control the primary pressure by the emergency gas evacuation system, the gas evacuation line and the pressurizer safety valves as well as the high and medium pressure injection systems.

The analysis of the cool-down was performed for two variants:

Variant 1: The initial phase of the cool-down is performed using all SGs;

Variant 2: The initial phase of the cool-down is performed with two SGs.

Variant 1: Cool-down using four steam generators

This variant covers the case when the cool-down is performed using all steam generators. The emergency feed water can be supplied to the steam generators in two ways: train 2 supplies steam generators 1 and 4 and train 3 feeds steam generators 2 and 3 or train 1 feeds all steam generators. For the latter additional operator actions are needed to provide emergency feed water injection to SGs 1 and 3.

The beginning of the cool-down is at 45 min after the initiating event and includes the following operator actions:

- Reset the feed water isolation signals for the isolated steam generators;
- Select a cool-down rate of 20 ^{o}C/h for all BRU-A.

It is assumed that during the cool-down the operators maintain the level in the pressurizer between 8 and 9 m (as required by the plant regulations) by using one or more pumps of the TQ3 system.

It is also assumed that the operator maintains the subcooling in the hot legs at the prescribed value by opening and closing of the YR line.

The primary circuit is cooled uniformly by natural circulation in all the loops. The potential for cooling through the secondary side is exhausted at 550 min (8 h 30 min after its beginning). After that the primary and secondary side parameters are stabilized.

12 hours after the initiating event the water inventory in the emergency feed water tanks is 592.3 m^3. Assuming (conservatively) that the emergency feed water flow remains constant after this moment, this volume is sufficient to remove the decay heat for at least 20 h 30 min more.

Variant 2: Cool-down using two steam generators

In this case the cool-down is started by selecting a cool-down velocity of 20^{o}C to the BRU-A facilities of SGs 2 and 4. The emergency feed water supply to these SGs is provided by the first EFW system train. It is assumed that SGs 1 and 3 remain isolated. The tank TX10D01 is empty 8 hours after the initiating event. Then the operator resets the isolation signal for SGs 1 and 3 and selects a cool-down rate of 20 ^{o}C/h for their BRU-A. The cool-down is continued by all steam generators, using TX trains 2 and 3.

The termination of heat removal by two of the steam generators leads to a decrease of the coolant flow in the respective primary loops and to loss of the natural circulation in these loops about 2 hours after the initiation of the cool-down. As a result the pressure, respectively temperature in the isolated steam generators remain high, the coolant temperature in the hot legs of loops 1 and 3 increases and, together with the loss of circulation, the subcooling in these loops decreases. Therefore the conditions for opening of the YR line are not met.

After the depletion of the first EFW tank the conditions in the different loops differ significantly. The pressure in SGs 2 and 4 is 0.2 MPa, while in the other two it is 5 MPa. The temperature in the cold legs of loops 2 and 4 is 122^{o}C, and in the hot legs - 140^{o}C.

In these loops a stable natural circulation is maintained (170 kg/s per loop). At the same time the temperature at the reactor inlet from loop 1 (with TQ3 injection) is 82^{o}C, from loop 3 it is about 143^{o}C, while in the hot legs the coolant temperature is 258 ^{o}C, which is only 24^{o}C lower than the saturation temperature. In order to prevent the injection of very cold ECCS water to the reactor, it is recommended to use a TQ3 pump, connected to a loop with natural circulation (in this case TQ23D01.

The potential for cool-down of the primary circuit by the secondary side in this case is exhausted nearly 14 hours after the beginning of the cool-down. 15 hours after the initiating event the water volume in the emergency feed water tanks is 513.7 m^{3}, which is sufficient to remove the decay heat for another 18 h 29 min.

The calculations show that in both variants of cool-down the systems and equipment available in case of loss of off-site power permit the cool-down of the plant to the required conditions (below 150^{o}C in the primary circuit).

The calculations performed for the two variants of cool-down of the plant can be used to evaluate the *risk of cold overpressurization* of the primary circuit.

At present the pressure-temperature limiting curves applicable for plant cool-down are under elaboration. According to the Technical Specifications for safe operation of the plant, the primary pressure shall not exceed 3.53 MPa when the coolant temperature is below 100^{o}C. This limitation is incorporated in the Hydropress protection. The input signal to the Hydropress protection is the average coolant temperature in the primary circuit, defined as the maximum of the average coolant temperatures in the loops. The output signals of the Hydropress protection system effect the primary make-up and let-down system and the reactor coolant pumps, but have no effect on the safety systems.

The Cold Overpressurization Protection system which is proposed to be installed at Kozloduy NPP follows the design principles, applicable to the modern western PWRs. This means that the input signal is the minimal temperature in the cold legs of the primary circuit. Comparing the minimal of the cold leg temperatures, predicted by the calculation of the cool-down process under LOOP conditions and the currently valid pressure-temperature limits, it is clear that if the cool-down is performed by two of the four steam generators, then the minimal cold legs temperature goes above the defined pressure-temperature limit. This means that there exists a risk for cold overpressurization. Due to the current input to the Hydropress protection, this risk will not be detected.

Use of the EFW system decay heat removal in case of BDBA

The beyond design basis accident which would demand the use of the emergency feed water system for at least 24 hours is the failure to put in operation the primary circuit residual heat removal system after cooling of the primary circuit below 150^{o}C, as prescribed in the plant procedures. The configuration of the RHR system is such, that no single failure can cause its inoperability. This justifies the classification of the event “Loss of off-site power with subsequent failure of the residual heat removal system” as a beyond design accident. For this reason the evaluation of the possibility to use the EFW system for decay heat removal for at least 24 hours was performed with the assumption that no other independent of the initiating event failures of safety systems and/or equipment occur.

The time for depletion of the emergency feed water tanks is estimated, assuming that after the above mentioned 12 (respectively 15 for variant 2) hours of cool-down, the emergency feed-water flow remains constant and that the initial water inventory in the tanks is minimal (3x450 m^{3}). If all the uncertainties are applied in a conservative direction, then the water inventory in the EFW tanks is sufficient to remove the decay heat for at least 28 h 45 min.

Conclusions and recommendations

The main conclusion from the study of the beyond-design basis accident “Loss of off-site power with a subsequent failure of the residual heat removal system in WWER-1000/320” is that the water inventory in the tanks of the emergency feed water system is sufficient to cool-down the plant and ensure the decay heat removal for at least 24 hours.

The above function can be fulfilled in case of failure of one of the pumps, as long as the connection between the tanks of the system is available.

Based on the results of the analysis of different variants of the transient, some recommendations can be given related to improvement of the plant safety:

<u>On the safety systems design</u>

The connection of the primary make-up/ let-down system (TK/TB pumps) to emergency power supply will permit the operators to reach the required shut-down boron concentration without initiating a leak from the pressurizer. The availability of the TK system in case of LOOP will give the possibility to use the cold spray to the pressurizer together with the respective controllers. This measure is included in the Modernization programme for Kozloduy units 5&6 and will be realized by the installation of an additional diesel-generator.

The installation of a system for cold overpressure protection will eliminate the possibility, illustrated in Variant 2 of the plant cool-down. This measure is also included in the Modernization programme.

<u>On the automatic of the safety systems</u>

The current setpoints for emergency feed water injection, especially the opening of the delivery side valves of the EFW pumps on low level in the steam generators result in rapid depressurization of the respective steam generator and its isolation both on the steam and on the feed water side. Besides, cold water is injected over a partially uncovered tube bundle. These effects could be avoided if, for the case of LOOP, the setpoints for opening of the delivery valves of the EFW pumps are modified and injection starts earlier.

<u>On the immediate operator actions</u>

The requirement to reach shutdown boron concentration in 30 minutes is rather strict. In the case of LOOP it should be relaxed to approximately 1 hour.

The requirement to maintain the subcooling in the cold legs at approximately 55 K, which is the value for normal operation, should be relaxed and the objective should be to prevent containment isolation.

<u>On the further operator actions</u>

In order to avoid the risk of violation of the pressure-temperature limiting curve for cold overpressurization it should be prescribed in the procedures to start the cool-down from hot conditions using all four steam generators.

Table 1: Sequence of events during the first 60 minutes

No	Event	Time (s)		
		Case 1	Case 2	Case 3
1.	Loss of off-site power: Turbine trip; Loss of power to RCP; Feed water pumps trip; Signal for diesel generators start	0	0	0
2.	Reactor trip	1.4	1.4	1.4
3.	Opening of BRU-A of SGs 1, 2 and 4 due to increase of SG pressure above 7.35 MPa	6.9	6.9	6.9
4.	Opening of BRU-A of SGs 3 due to increase of SG pressure above 7.35 MPa with delay for DG (motor of the valve is II cat)	15	15	15
5.	ASSS I program starts	15	15	15
6.	Start of (only relevant systems are indicated): - TQ14(24,34)D01 (5-th s of ASSS) - TQ13(23,33)D01 (5-th s)	20	20	20
7.	Start of TX10(20,30)D01 (40-th s of ASSS)	55	55	55
8.	OA: Close recirculation lines of TQ14,24,34D01	900	900	900
9.	OA: Open YR51S01 and YR63S01 (for the conditions see description of the cases)	-	900- 1330 2220-	1800-
10.	Beginning of EFW injection to the SGs (all trains available) – SG1 – SG2 – SG3 – SG4	 1425 1039 1478 1039	 1456 1041 1510 1041	 1425 1039 1478 1039
11.	TQ13,23,33D01 start injection to the primary circuit	-	2250	2240
12.	Pressurizer level > 8 m (forbidding signal to close TQ13(23.33)S08 disappears)	3380	2460	2450
13.	Isolation of SG due to pressure in the steam line < 5 MPa and Δp at the check valve <–0.196 MPa: – SG 1 – SG 2 – SG 3 – SG 4	 1998 - 1993 -	 2023 2700 2018 2587	 1992 2675 1987 2555
14.	Closing of BRU-A – SG 1 – SG 2 – SG 3 – SG 4	 1430 1045 1480 1045	 1460 1045 1400 1045	 1430 1045 1480 1045
15.	Beginning of cyclic operation of the first pressurizer safety valve	3400	-	-

OA = Operator action

Table 2: Some plant parameters at 45 and at 60 min

Case / Parameter	At 45 min			At 60 min		
	1	**2**	**3**	**1**	**2**	**3**
Total mass discharged by YR (kg)	0	6834	6490	0	24265	23908
Two-phase flow in YR lines after (s)		-	-	-	2720	2710
Total mass injected by the TX pumps (kg)	103583	103054	102918	104098	103054	102918
Water volume in SGs (m3)	271	268	267	277	270	270
Total mass injected by TQ4 (kg)	8996	8996	8996	13494	13494	13494
Total mass injected by TQ3(kg)	0	34688	35015.5	0	45002	44893.5
CH3BO3, g/l (core inlet)	1.435	8.16	8.22	2.05	7.88	7.82
CH3BO3, g/kg (core)	1.82	9.56	9.64	2.67	9.99	9.93
CH3BO3, g/l (pressurizer)	0.114	4.6	4.62	0.94	6.67	6.61
$T_{average}$ in the primary circuit, ^oC	280.22	267.43	267.42	290.34	275.67	275.95
Primary coolant inventory, kg	252269	280437	281090	256003	277755	277969.7

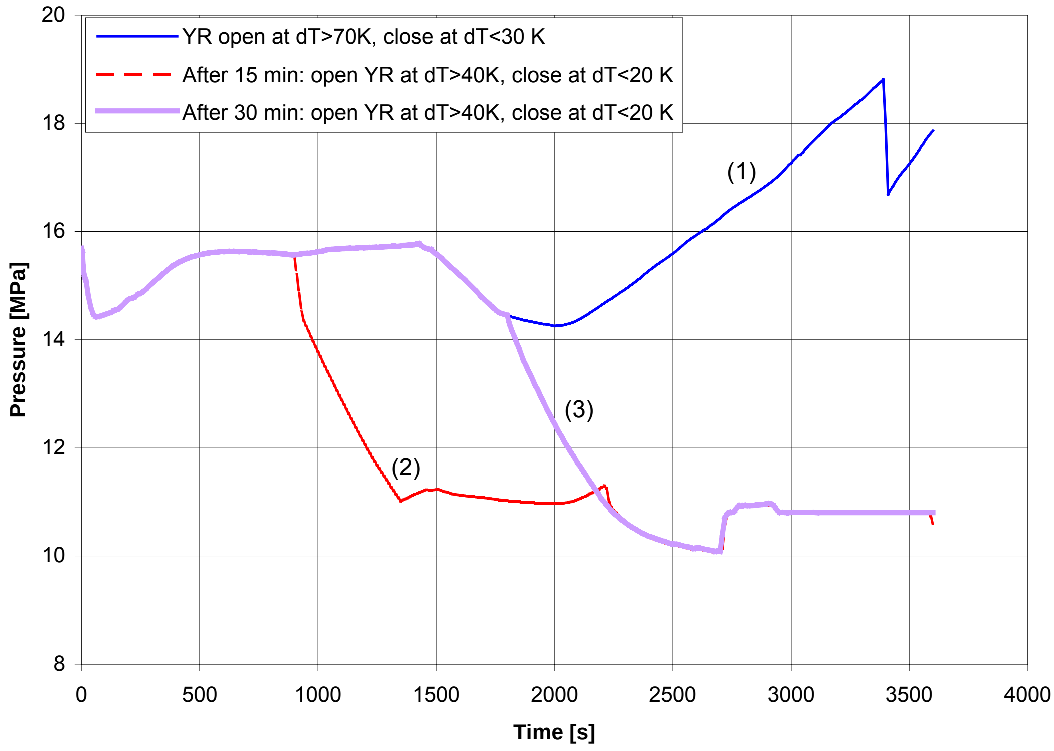

Fig. 1. Primary pressure during the first 60 min of transient

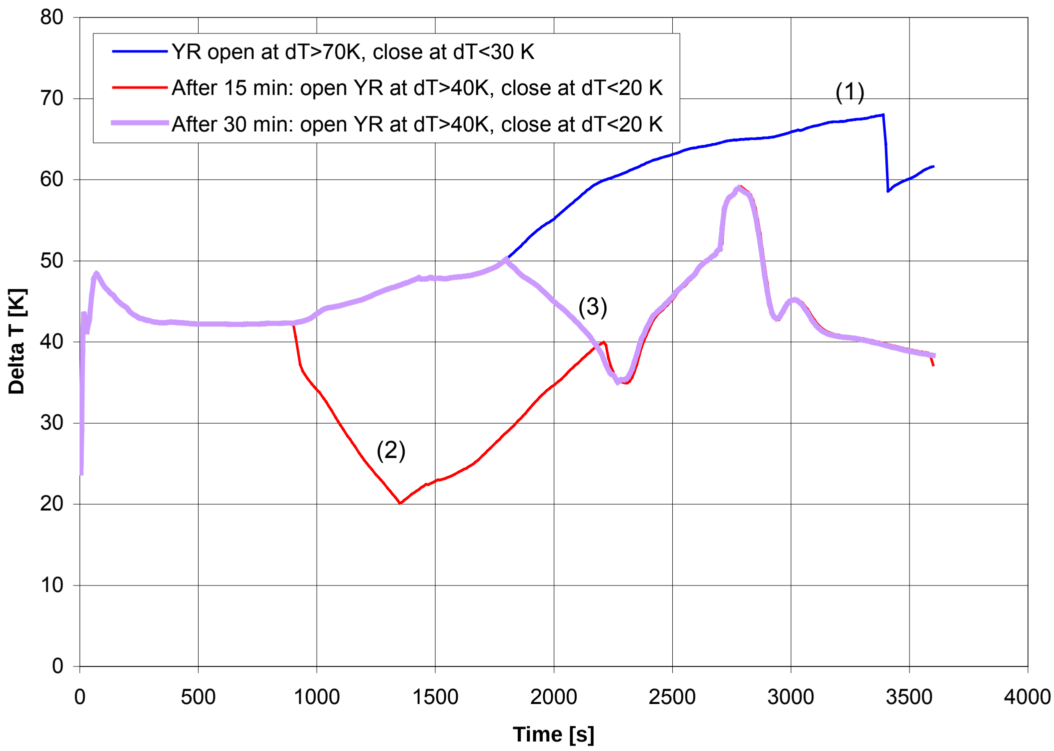

Fig. 2. Difference between the saturation temperature and the hot legs temperature during the first 60 minutes

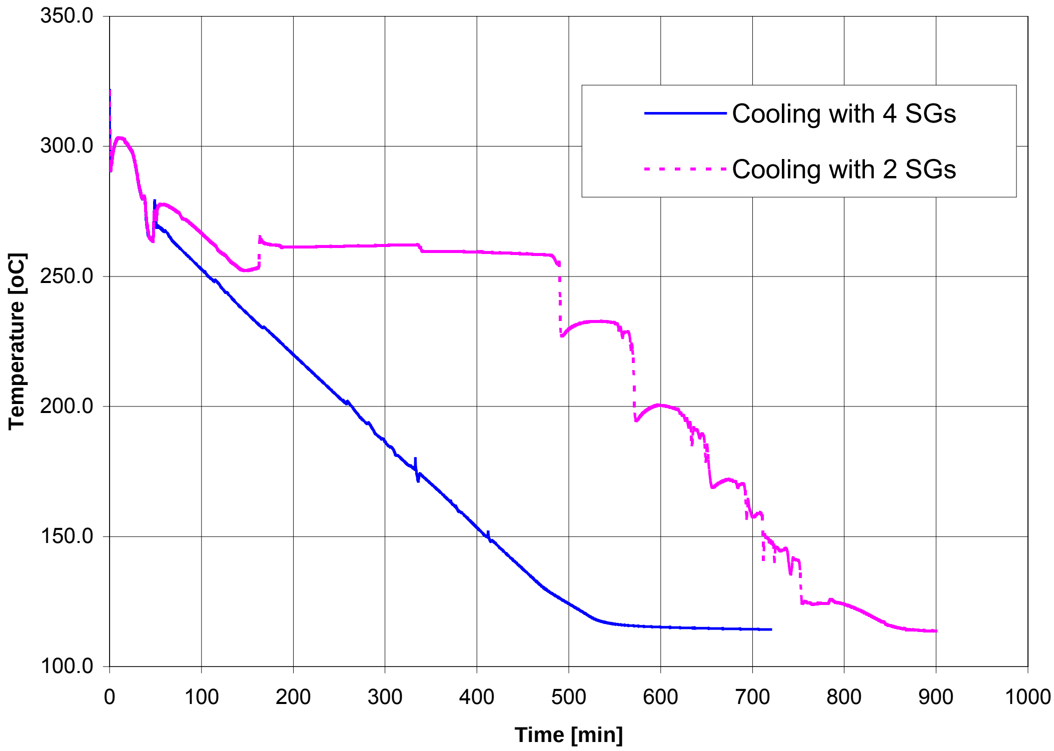

Fig. 3. Average coolant temperature in the primary circuit (defined as the maximum of the average coolant temperature in the loops)

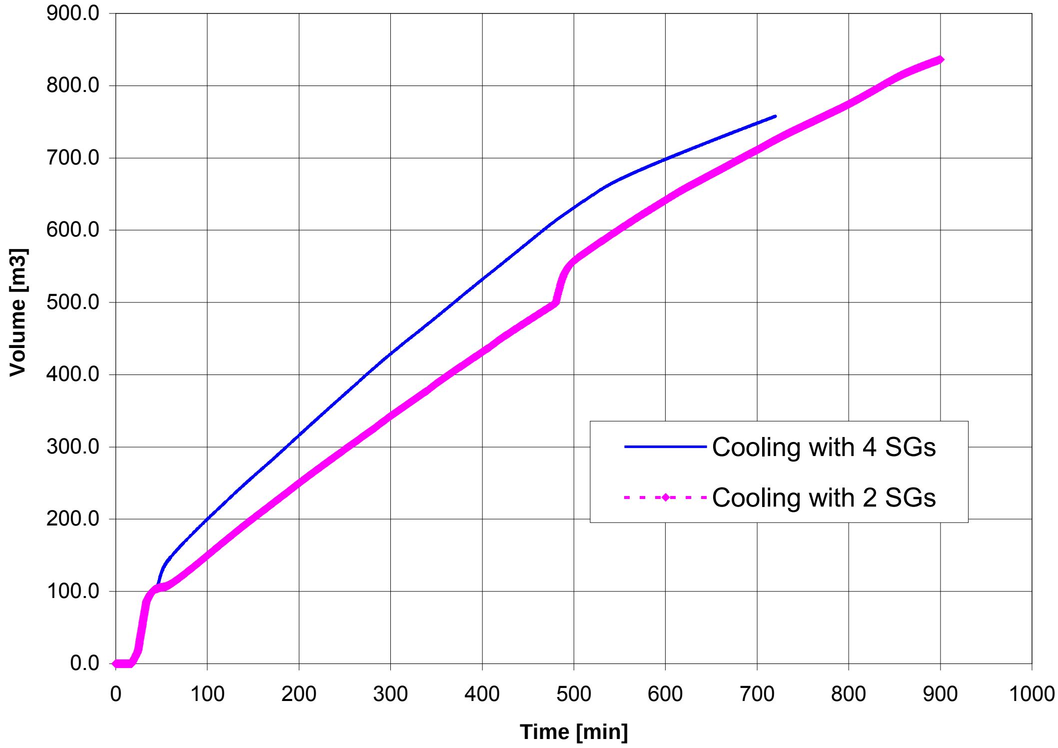

Fig. 4. Water volume discharged from the emergency feed water tanks

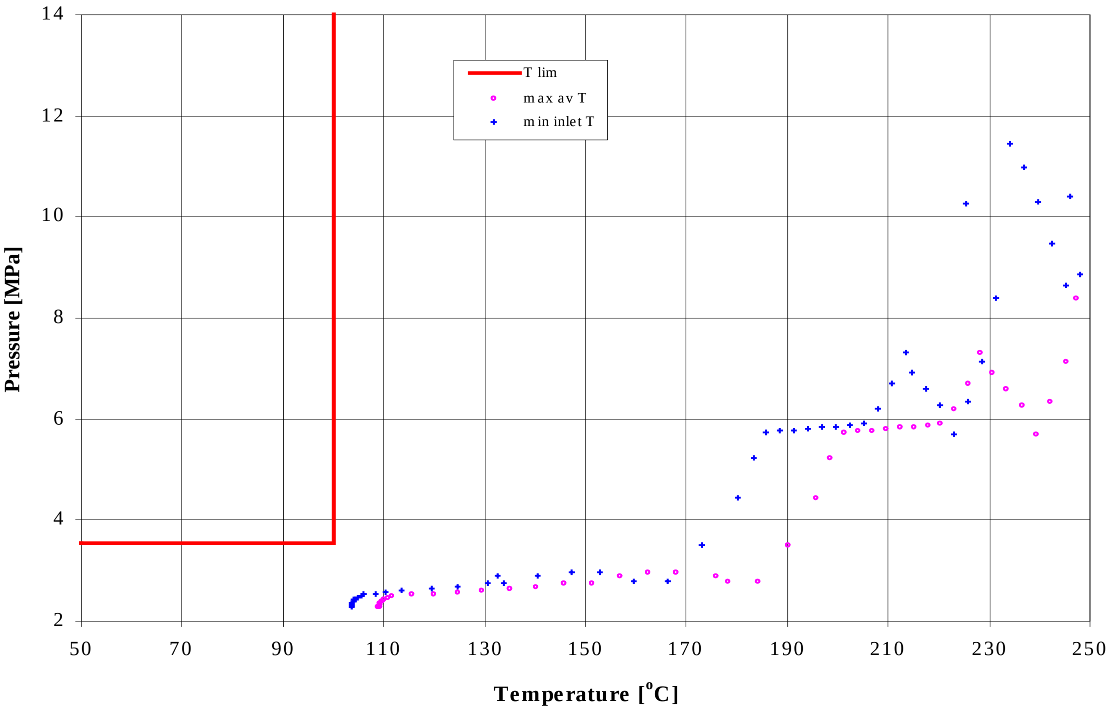

Fig. 5. Comparison of the representative coolant temperatures with the pressure-temperature limit – cooling with 4 SGs

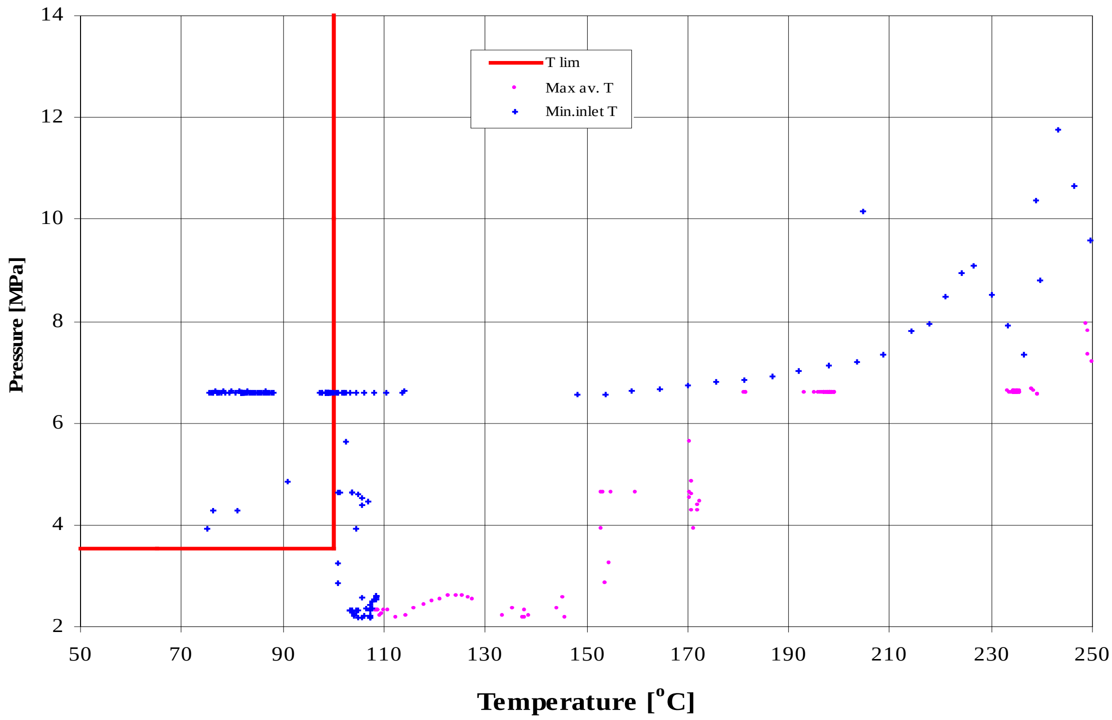

Fig. 6. Comparison of the representative coolant temperatures with the pressure-temperature limit – cooling with 2 SGs