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Preliminary Analyses of the LOCA 200 mm for NPP Kozloduy, Units 1-4

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Abbreviation

DBA	Design Base Accident	TH, THA	Thermo-Hydraulic Analysis
BOC	Beginning Of Cycle	TSV	Turbine Stop Valve
CL	Cold Leg	VVER, WWER	Pressurized Water Reactor
DG	Diesel Generator	μ_{be}	Best estimate discharge coefficient
ECCS	Emergency Core Cooling System	μ_{cons}	Conservative discharge coefficient
EOC	End Of Cycle	μ_{max}	Maximal discharge coefficient
HPIP	High Pressure Injection Pump	μ_{red}	Reduced discharge coefficient
INEEL	Idaho National Engineering & Environmental Laboratory	μ_{sub}	Sub-cooled discharge coefficient
LOCA	Loss Of Coolant Accident	μ_{tp}	Two-phase discharge coefficient
LOOP	Loss Of Off-site Power	μ_v	Steam discharge coefficient
LPIP	Low Pressure Injection Pump	H_{prz}	Pressurizer level
MCP	Main Circulation Pump	P_1	Primary pressure
NPP	Nuclear Power Plant	P_{box}	Confinement pressure
PRZ	Pressurizer	Q_{res}	Decay heat
SG	Steam Generator	T_{cl}	Cladding temperatures
TG	Turbine, Turbo-Generator	T_{cl}^{max}	Maximal cladding temperatures

Introduction

As it is known the DBA for NPP with VVER-440(V230) reactors is Cold Leg LOCA 32 mm.

Performed recent analyses showed that existing ECCS of the units 1-4 of NPP Kozloduy, equipped with such type of reactors, coupe with ruptures of real piping of RCS up to 200 mm.

In this article the TH analyses of the following LOCA are discussed:

a. rupture of LPIP line for unit 3(CL LOCA 200 mm);
b. rupture of surge line for units 1 and 3, which results in LOCA 2x209 mm.

There were several runs with different boundary condition performed for analyzed cases. Parametric (sensitivity) study was focused on the axial power distribution in the core (BOC and EOC), discharge coefficients and time of units blackout.

Methodology

► *Primary and secondary side modeling*

The six legs were defined as three lumped legs – two of them for modeling the mechanical rundown of MCP, one (failed) and three legs for modelling of the electro-mechanical rundown of MCP.

The core was modelled as a system of three channels – bypass, hot channel with a hot fuel rod and the average channel representing the rest part of the core.

The heated part of the fuel elements was moddeled by five axial sectors. The downcomer of the reactor was divided into three parts in accordance with the number of the limpeded legs.

The SG bundle package was presented as five axial sectors considering its relatively low impact during large LOCA.

The model was detaily revised and approved by experts from INEEL laboratory (USA). The adequacy of the moddeling was checked against the requirements for

modelling of reactor facilities using this code (RELAP5) as well as the correctness of input data interpretation [1].
The nodalization scheme of primary and secondary side is shown on Fig.1-3.

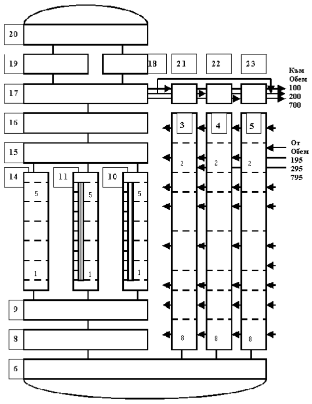

Fig.1 Model of reactor

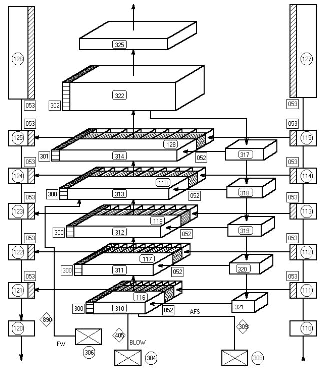

Fig.2 Steam generator model

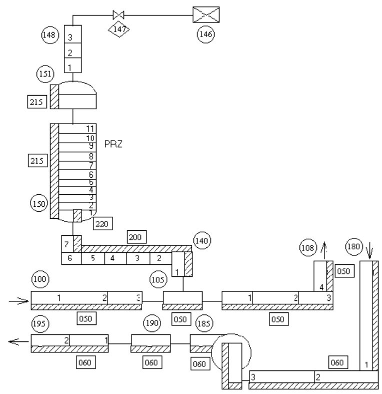

Fig.3 PRZ loop model

► *Conservative assumptions*

⇨***DG loading sequence [2]***

Unit 1 and 3 — Table 1

t_o^1- time of LOOP $t_o=t_o^1+1$ s	**Unit 1 $t_1=t_o+31$ s Unit 3 $t_1=t_o+35$ s**	**$t_2=t_1+5$ s**	**$t_3=t_1+10$ s**	**$t_4=t_2+15$ s**	**$T_5=t_3+15$ s**
DG start	DG ready, automatic start of loading sequence	HPIP available	LPIP available	HPIP injection starts, if condition is met.	LPIP injection starts, if condition is met.
		Unit 1 and 3	Unit 3	Unit 1 and 3	Unit 3

⇨ ***Conservative initial parameters of the units***

Table 2

Parameter	**Conservative correction of the nominal value**
Primary circuit maximal pressure	+2%
Pressurizer maximal level	+5%
HPIP Minimal capacity	-5%
LPIP Minimal capacity	-5%
Maximal residual energy release	Conservative significances of Q_{res}. (ANS+20%)
Maximal delay of A3-1 signal - at P_1 - at H_{prz}	 +1.5 s +2.0 s
Maximal delay of the signal for activating the HPIP - at P_1 - at H_{prz}	Pressure setpoint -2% Level setpoint - 5 %

Table 2(cont.)

Parameter	Conservative correction of the nominal value
MCP's rundown	-2%
Maximal tempearture in Emergency Water Tank	60°C
SG maximal pressure	+2 %
Maximal setpoint of the SG savety valves	+2 %
Minimal coolant flow rate in reactor	-2%

➪ ***Residual energy release [2]***

Residual energy release in core ANS 79-1+20%

Table 3

Time, s	0.	1.	5.	10.	20.	50.	100.	300.	1000.	1800.	4000.
$Q_{res,}$ %	8.36	7.89	6.85	6.23	5.59	4.77	4.18	3.21	2.64	2.25	1.77

➪ ***Discharge critical break flow coefficients***

Table 4

Break flow	**Real - (μ_{Be}) [3]**	**Conservati-ve ($\mu_{cons.}$)***	**Maximal - (μ_{max}) [4]**	**Reduced- (μ_{red}) [4]**
Steam - (μ_v)	0.82-0.88	0.97	1.2	1.2
Two-phase mixture- (μ_{TP})	0.8-0.88	1.06	1.4	1.2
Subcooled water - (μ_{sub})	0.9-0.98	1.18	1.2	1.2

**Note*: The values of the discharge critical break flow conservative are obtrained from the real values considering the correctness of measurings of the critical flow rate. At steam leakage, it is estimated at 10%, and at two-phase mixture and subcooled water – 20% [3]. In reduced coifficients is decreased only μ_{TP},in comparison with the maximal values.

➪ ***Emergency Core Cooling System configuration and injection in primary circuit at LOCA 200 mm and 2x209 mm***

Table 5

Units №	**ECCS availability during blackout**	**Failures**	**Injection points**	**Scheme of emergency feedwater**
I-II	Two HPIP	DG-11 or DG-13 (delay of the start of the second HPIP)	MCP suction and delivery pipes	Each HPIP supplies the six legs
III-IV	Three HPIP	One channel of ECCS*	MCP suction and delivery pipes	Each HPIP supplies two legs
	Three LPIP		Between MIV and the inlet nozzle of the reactor	Each LPIP supplies one leg

**Note:* 1. ECCS of units III and IV includes three channels. Each channel includes one HPIP and one LPIP.
2. At LPIP pipeline rupture is assumed that one channel of ECCS is lost. In this case only one channel of ECCS remains effective.
3. For rupture of pipelines, connecting the pressurizer with MCP, both channels of ECCS are effective.

⇨ Pressure in the SG containment

The pressure in the confinment for the purposes of THA for the primary circuit it is assumed conservatively the minimal and equal to 1.013 bar (atmosphere pressure) and constant in accordance with the requirements for the licencing analyses.

⇨ Temperature of the water in the Emergency Water Tanks

The temperature of the water in the Emergency Water Tanks conservatively is assumed as a constant one and equal to 60°C.

NPP data

➤ *Unit initial condition [2]*

Table 6

Parameter	Value
Thermal reactor power, MW	1402.5
Rector inlet temperature, °C	265.0
Primary ressure, MPa	12.36
Reactor flow rate, m^3/h	Unit 1 – 44600; Unit 3 - 44500
Steam flow to the TG, t/h	2700
SG pressure, MPa	4.67
Temperature of SG feed water, °C	220
Pressurizer level, m (unit 1, 2)	5.15
Pressurizer level, m (unit 3, 4)	5.33
Bypass flow, %	9.5

➤ *SCRAM signals [2]*

Table 7

Units №	SCRAM signals		
	P_1, kg/cm^2	H_{prz}, mm	P_{box}, kg/cm^2
1-2	115.0	-2700	0.2
3-4	115.0	900 (H_{cp})	0.2

➤ *ECCS setpoint [2]*

Table 8

Units №	ECCS setpoints		
	HPIP		LPIP
	P_1, kg/cm^2	H_{prz}, mm	P_1, kg/cm^2
1-2	105.0	-2560	-
3-4	105.0	900	7.0*

*7.92 bar – abs. primary pressure

Accident scenarios for break of real pipes with equivalent diameter 200 mm and 2x209 mm

➤ <u>*Pressurizer surge line rupture for Units 1 and 2*</u>

Event sequence:

τ_0=0.0 s -	PRZ surge line rupture (LOCA 2x209 mm)
$\tau_1=\tau_0+\tau^{i}$	SCRAM by P_1 or H_{prz} (first signal)
$\tau_2=\tau_1+\tau^{ii}$	Blackout at SCRAM. TSV closure. MCP rundown. (two MCP – mechanical and four MCP – electro-mechanical) SG feed water is stopped
$\tau_3=\tau_2+\tau^{iii}$	Start of two HPIP, according DG loading program and begin to inject when the set point is reached.

➤ <u>*LPIP pipe line rupture for Units 3 and 4*</u>

Event sequence:

τ_0=0.0 s -	LPIP pipe line rupture (LOCA 200 mm)
$\tau_1=\tau_0+\tau^{i}$	SCRAM by P_1 or H_{prz} (first signal)
$\tau_2=\tau_1+\tau^{ii}$	Blackout at SCRAM. TSV closure. MCP rundown. (two MCP – mechanical and four MCP – electro-mechanical) SG feed water is stopped
$\tau_3=\tau_2+\tau^{iii}$	Start of one HPIP, according DG loading program and begin to inject when the set point is reached.
$\tau_4=\tau_2+\tau^{iii}$	Start of one LPIP, according DG loading program and begin to inject when the set point is reached.

Analyses performed for determination of maximal cladding temperatures

Matrix of analyses for Unit 1 and Unit 3 is presented in Table 9 and Table 10.

Notes:
1. μ_{max}, μ_{red} – maximal and reduced coefficients of break flow
2. μ_{Be}, μ_{cons} – Realistic and conservative coefficients of break flow
3. T_{cl}^{max} – Maximal hot fuel rod cladding temperatures
4. BOC, EOC – Beginning and End of Cycle
5. HPIP-1(2) – Beginning of first HPIP primary injection (second)

NPP Kozloduy, Unit 1, Comparative analysis of different cases for LOCA 2x209 Table 9

Failure of DG-13				**Failure of DG-11**									
Blackout at the SCRAM				**Blackout at the TSV closure**				**Blackout at the SCRAM**					
Case №	T_{cl}^{max}, °C	HPIP-2, s	HPIP-1, s	Case №	T_{cl}^{max}, °C	HPIP-2, s	HPIP-1, s	Case №	T_{cl}^{max}, °C	HPIP-2, s	HPIP-1, s		
-	-	-	-	Case 1.2	570	57	57	Case 1.1	582	57	57	μ^{cons}	**BOC**
-	-	-	-					-	-	-	-	μ^{Be}	
Case 2.4	**828.**	**74.**	**52.**	Case 2.2	507	57	57	Case 2.1	811	57	57	μ^{cons}	**EOC**
				-	-	-	-	Case 2.3	800	57	57	μ^{Be}	

NPP Kozloduy, Unit 3, Comparative analysis of different cases for LOCA 200 mm and LOCA 2x209 mm Table 10

LOCA 2x209 mm				**LOCA 200 mm**									
Failure of one ECCS channel. Two HPIP , Two LPIP in operation				**Failure of one ECCS channel. One HPIP and one LPIP in operation**									
Blackout at SCRAM				**Blackout at TSV**				**Blackout at SCRAM**					
Case №	**T_{cl}^{max}, °C**	**LPIP, s**	**HPIP, s**	**Case №**	**T_{cl}^{max}, °C**	**LPIP, s**	**HPIP, s**	**Case №**	**T_{cl}^{max}, °C**	**LPIP, s**	**HPIP, s**		
-	-	-	-	Case 3.2	530	347	56	Case 3.1	700	317	56	μ_{max}	BOC
-	-	-	-					-	-	-	-	μ_{red}	
Case 5.1	550	200	56	Case 4.2	640	336	56	**Case 4.1**	**800**	**311**	**56**	μ_{max}	**EOC**
-	-	-	-	-	-	-	-	Case 4.3	760	334	56	μ_{red}	

Results of analyses

The physical phenomena and results of analyses will be presented for the following two cases, where the maximal cladding temperature is obtained.

▸ *Case 2.4*

The sequences of the events are given in Table 11, and the change of the parameters is given on fig.1.1.-1.4.

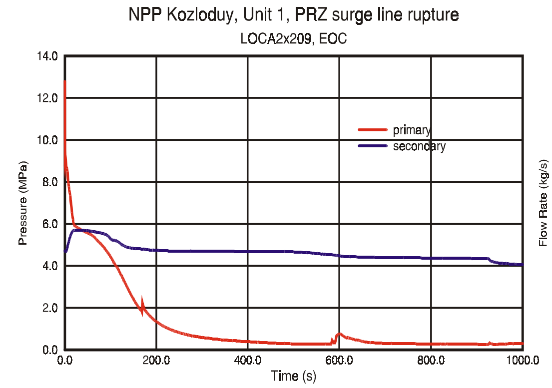

Fig.1.1 Primary and secondary pressures

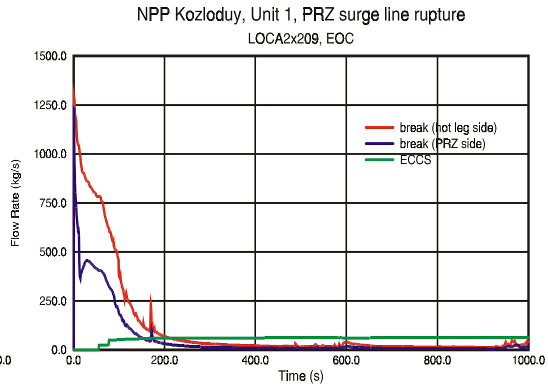

Fig.1.3 PRZ surge line break flow rate and ECCS flow rate

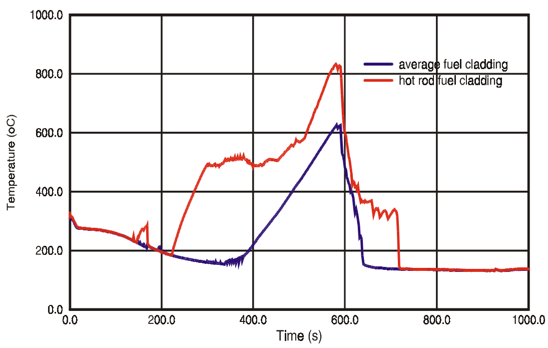

Fig.1.2 Maximal cladding temperatures

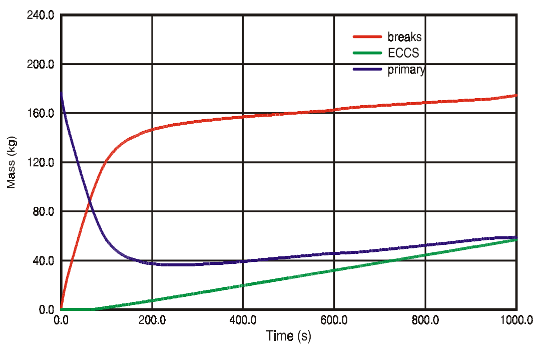

Fig.1.4 Primary inventory, Breaks outflow and ECCS inflow mass

Table 11

Events	Time, s
1. Pipe rupture 2x209 mm, conecting the pressurizer with primary circiut	0.0
2. “Primary circuit pressure<11.15 MPa”	1.9
3. Actuation of SCRAM at p.2. Blackout. Closure of TSV. MCPs shutdown (2 MCPs at mechanical and 4 MCPs at electromechanical rundown)	3.4
4. First HPIP readiness. First HPIP start to inject	56.0
4. Second HPIP readiness. Second HPIP start to inject	78.0
5. Maximal temperature of the fuel cladding ~828°C	~578.0
6. Core is cooled	~720.0

The main principles of the accident process is characterized with the following more important peculierities.

As a result of the fluid lost the level of the two-phase mixture in the core drops and achieved zero at 170th s. This causes sharp increase of the temperature in the hot fuel rod up to ~600°C at 350th s

But in this moment the flow rate of HPIP compensates the break and the level in the core is increased to 0.3-0.5 м. This causes increase of the generation of steam in the bottom part of the core and decreases of the real volume of steam content in the volumes above the quench front. As a result the maximal temperature of the hot fuel rod drops to 550°C. Because during the fuel rod cooling in volumes 3, 4 and 5, across the core height, is realized in disperse flow, the availability of the preheated steam, causes intensive evaporation of the liquid fluid drops in the upper part of the core (volume №5), leading to a cooling mode in conditions of convection to preheated steam. This is a reason for existence of second period, with bigger gradient of increasing of T_{cl} after 450th s After this moment, the positive mass balance in primary circuit and the decrease of Q_{res}, causes effective cooling of fuel rod, as a result of quick movement at the quench front. About 600th s, it reaches the upper part of fuel rod and the temperature sharply drops down, after it has reached its maximal value of 811°C.

➤ *Case 4.1*

The sequences of the events is given in Table 12, and the change of parameters is presented on figure 2.1-2.4.

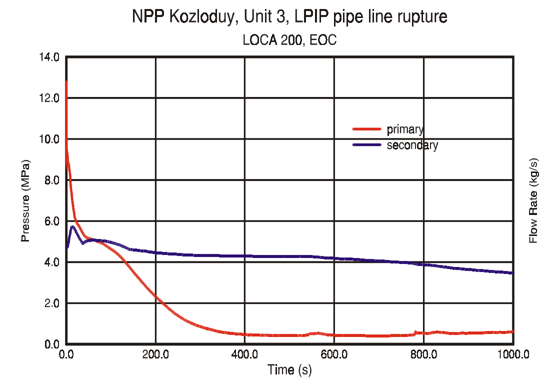

Fig.2.1 Primary and secondary pressures

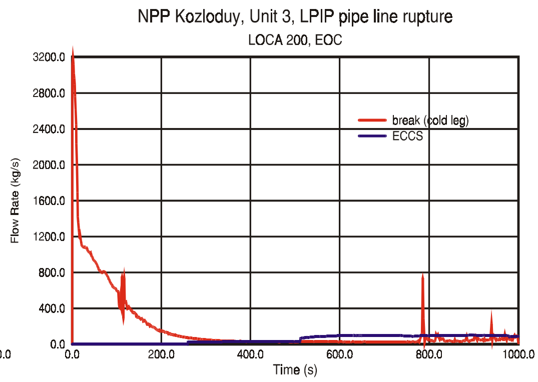

Fig.2.3 LPIP pipe line break flow rate and ECCS flow rate

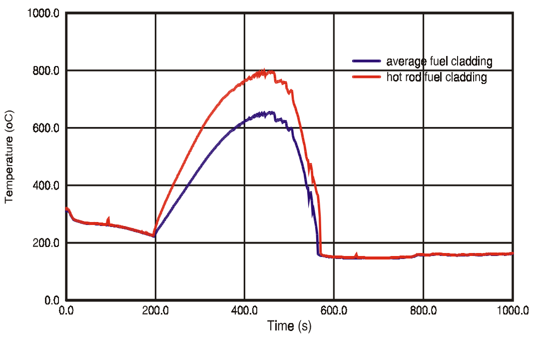

Fig.2.2 Maximal cladding temperatures

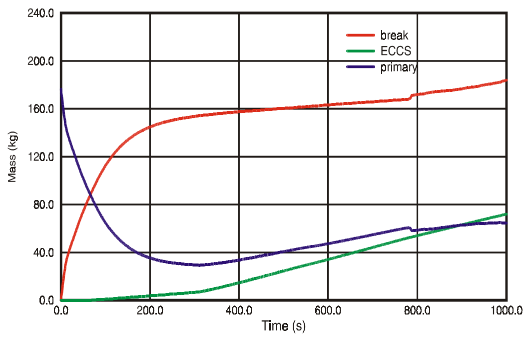

Fig.2.4 Primary inventory, Break outflow and ECCS inflow mass

As a result of break flow, the pressure drops down and reaches the set points of SCRAM actuation and HPIP at signal “low pressure in primary circuit”. Unit blackout is assumed at SCRAM and TSV closed at the same time, the feed water of SG is stopped and it is realized mechanical and electromechancal rundown of MCP, respectively of 2 and 4 of them.

After equilizing the pressure in primary circuit with the one in SG, they stop to remove energy from primary circuit, i.e. the crossection of the rupture is big enough for decay heat removal from the core.

Table 12

Event	Time, s
1. Pipe 200 mm rupture, conecting LPIP with primary circiut	0.0
2. “Primary circuit pressure<11.15 MPa”	2.1
3. SCRAM actuating under item 2. Black out. Turbine stop valves closure. MCPs shutdown (2 MCPs at mechanical and 4 MCPs at electromechanical operation)	3.6
4. HPIP readiness. One HPIP starts injecting in primary circuit	60.2
5. LPIP readiness	65.2
6. “Primary circuit pressure <0.792 MPa”. LPIP starts injecting in primary circuit	~311.0
7. Maximal temperature of the fuel cladding ~800°C	~442.0
8. Core is cooled	~580.0

In spite of the injection with 1 HPIP, which starts 56 s after the black out, fluid loss in primary circuit causes futher decrease of the core level.
About 200th s, the level is not high enough and the amount of the generated steam, its flow rate respectively decreases so much, that it is not possible to cool effectively the fuel rod. This is shown where after 190th s, the flow rate at the core outlet is actualy zero, as a result of which the temperature of the fuel rod cladding and of the fuel starts to increase, achieving maximal values of T_{cl}=800°C at 470th s
The fluid level in the core reaches its minimal value at 310th s, after which it starts to grow as a result of switching on the LPIP in primary circuit. Water penetration from the ECCS changes the flow of the two-phase mixture in the core, as at 470th s the quench front reaches the fuel rods area with maximal temperature, which decreases sharply.

Conclusions

1) Performed licensing analyses showed that a maximal fuel cladding temperature is obtained for EOC, maximal discharge coefficients and in case of LOOP at SCRAM signal.
2) The maximal fuel cladding temperatures for different units are as follows:
- LOCA 2x209 mm (unit 1) – T_{cl} = 828 ^{o}C;
- LOCA 2x209 mm (unit 3) – T_{cl} = 550 ^{o}C;
- LOCA 200 mm (unit 3) – T_{cl} = 800 ^{o}C.
3) The acceptance criteria for LOCA [5] are satisfied.

References

[1] Review of ENERGOPROEKT RELAP5 input models for Kozloduy – SMM-06-99, INEEL, April 21, 1999
[2] Package of NPP Kozloduy initial data.
[3] M.Marinov, K.Avdjiev, Thermo-hydraulic safety aspects of VVER-440 reactors, Heron press, Sofia, 1999.
[4] TH analyses of the Bohunice V-1 selected CL DBA LOCAs, PHARE NSO1, VUJE, Trnava, 1996.
[5] Guidelines for accident analyses of WWER NPP, IAEA EBP-WWER-01, OEC, 1995
[6] Groudev P., Hadjiev, V., and Pavlova, P., Analyzing SBLOCA in Support of EOP Development, BNS, Sofia 18-19 November 1998.