Development of coupled thermohydraulics-neutron kinetics models with RELAP5-3D code for VVER reactors

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Introduction

RELAP5-3D code models for Rivne NPP unit 1 (VVER-440), Zaporizhzhya NPP unit 5 (VVER-1000) and Kozloduy NPP unit 6 (VVER-1000) have been developed within the framework of the Ukraine VVER Special Transient Analysis project [1]. For the development of RELAP5-3D VVER reactor models the corresponding RELAP5/Mod3.2 code models, developed and validated under the US DOE International Nuclear Safety Program, were used. One-dimensional models of the reactor pressure vessel and its internals have been replaced with their three-dimensional models for original complete plant models. More detailed description of RELAP5-3D VVER models is presented in this paper.

RELAP5-3D code [2] has multi-dimensional thermal-hydraulic and neutron kinetics modeling capabilities. This removes any restrictions with respect to applicability of this code to full scope operational transients. Besides RELAP5-3D users may activate a new set of CHF correlations based on data available in the Czech Republic data bank [3]. These correlations replace the "CHF Table Look-up" method. Differences in the output of the PG and the table lookup method were estimated.

One of the main purposes of the project is the application of the multi-dimensional coupled thermohydraulics-neutron kinetics models to analyzing the specific VVER transients in support of the In-Depth Safety Analysis (ISA) projects in Ukraine. The International Nuclear Safety Center of Russian Minatom (RINSC) has provided the authorized remote account on RINSC SGI Origin 200 computer storing RELAP5-3D code for National University of Kyiv.

Rivne NPP unit 1 RELAP5-3D model

For the development of Rivne NPP unit 1 RELAP5-3D model the RELAP5/Mod3.2 input deck, developed and validated by Energorisk Ltd. within the framework of the US DOE Rivne NPP ISA project [4], and WIMS-generated cross sections libraries, prepared by National University of Kyiv [5], were used. The RELAP5-3D model nodalization for reactor pressure vessel and its internals is shown in Fig.1.

Basic principle of reactor pressure vessel RELAP5-3D model deals with azimuthal subdivision of the reactor vessel into 6 sectors that corresponds to sectors of a reactor core symmetry. Such model allows to take into consideration individual properties of each loop. The axial modeling of the RELAP5/Mod3.2 reactor pressure vessel remains the same. The downcomer was sudivided into 8 segments in a azimuthal direction because of ECCS system design features.

As source data for "steady-state validation" of the RELAP5-3D model the plant nominal design steady state data were used. The main technological parameters are shown in Table 1. As shown in Table 1, calculated parameters are in a good agreement with design ones. Besides the RELAP5-3D axial and radial relative power of the reactor core coincide with similar plant calculated data within the limits of 5 %. A "transient validation" of the RELAP5-3D model including research of sensitivity to the reactor model nodalization is planned.

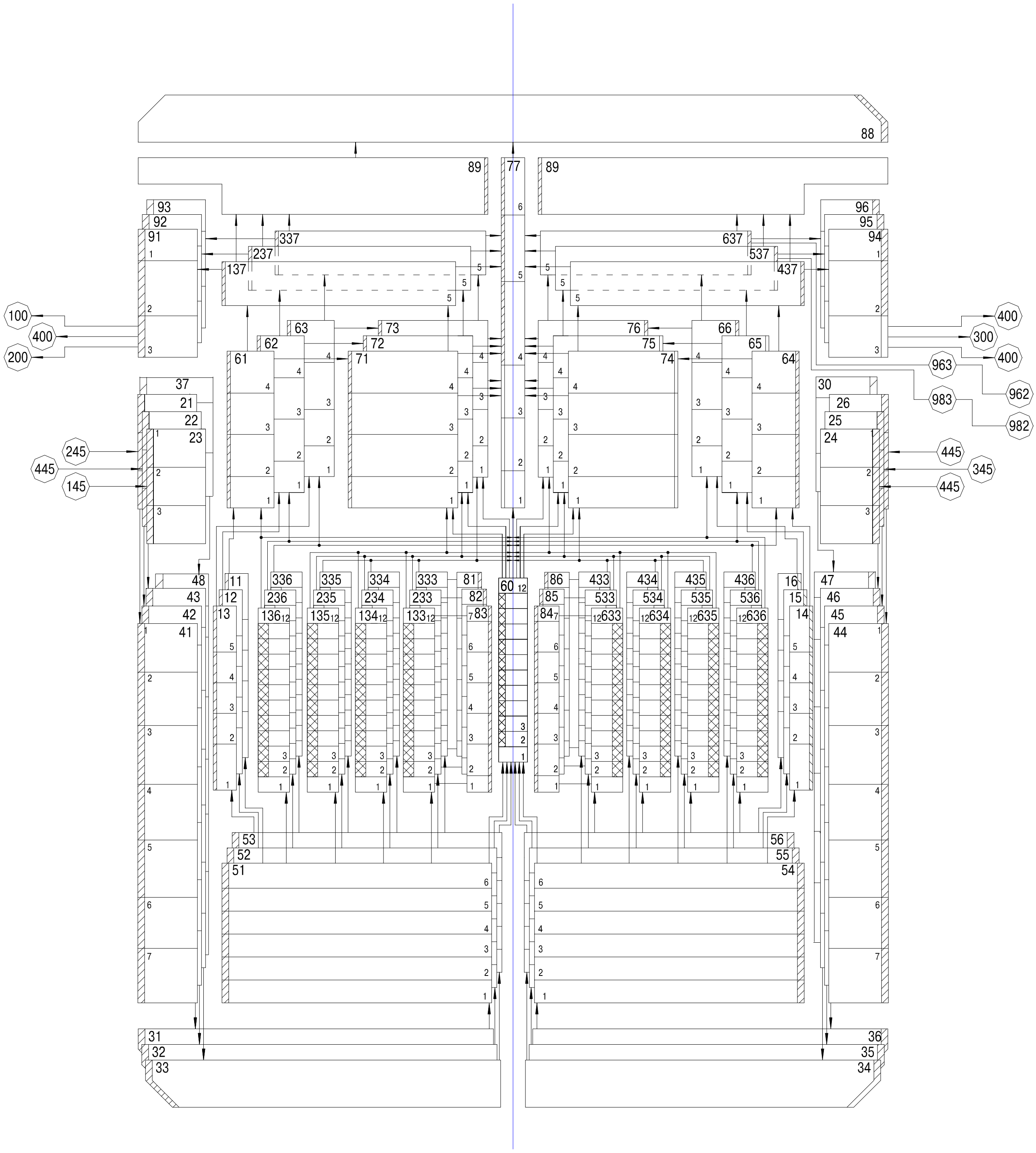

Fig.1. Rivne NPP unit 1 RELAP5-3D reactor model nodalization.

Table 1. Rivne NPP unit 1 design and RELAP5-3D calculated steady state parameters.

Parameter	Units	Rivne unit 1 design data	RELAP5-3D calculated data
Thermal reactor power	MW	1375±27	1375
Pressure at the reactor outlet	kgf/cm^2	124±1.2	124.4
Pressurizer level	m	5.96	5.955
Coolant flow through the reactor	m^3/h	39600±400	39650
Reactor inlet temperature	°C	≤267	263.3
Reactor outlet temperature	°C	297.9	298.5
Pressure differential across the reactor	kgf/cm^2	3.05±0.10	3.02
Pressure differential across the core	kgf/cm^2	2.1±0.1	2.1
Pressure differential across the MCPs	kgf/cm^2	4.35-4.65	4.50
Primary pressure differential across the SGs	kgf/cm^2	0.8	0.74
Pressure in SGs	kgf/cm^2	46	45.9-46.0
SG level	m	2.105±0.050	2.10÷2.11
Coolant temperature at the SG “hot” manifold inlet	°C	297±2	298
Coolant temperature at the SG “cold” manifold outlet	°C	267±2	267
Feed water temperature	°C	223±2	223
Steam capacity	t/h	450	440÷450

Zaporizhzhya NPP unit 5 RELAP5-3D model

For the development of Zaporizhzhya NPP unit 5 RELAP5-3D model the RELAP5/Mod3.2 input deck, developed and validated by Energoatom Engineering Service (EIS) and Energorisk Ltd. within the framework of the US DOE Zaporizhzhya NPP ISA project [6], and WIMS-generated cross sections libraries, prepared by National University of Kyiv [5], were used. The RELAP5-3D model nodalization for reactor pressure vessel and its internals is shown in Fig.2.

As source data for “steady-state validation” of the RELAP5-3D model the plant nominal design steady state data were used. The main technological parameters are shown in Table 2. As it is shown in Table 2, the parameters calculated are in a good agreement with design ones. Besides the RELAP5-3D axial and radial relative power of the reactor core coincide with similar plant calculated data within 5 % uncertainties.

It might be necessarily noted, that the original ISA RELAP5/MOD3.2 model has certain limitations regarding to simulation of the asymmetric loop behavior (actual 4-loop reactor coolant system was represented by 3-loop input model). A “transient validation” of the RELAP5-3D model including research of sensitivity to the reactor model nodalization is planned. More detailed three-dimensional description of the flow and temperature distributions in the transient situation will allow to reproduce more accurately the complete picture of events that may occur in the associated reactor regions throughout a transient.

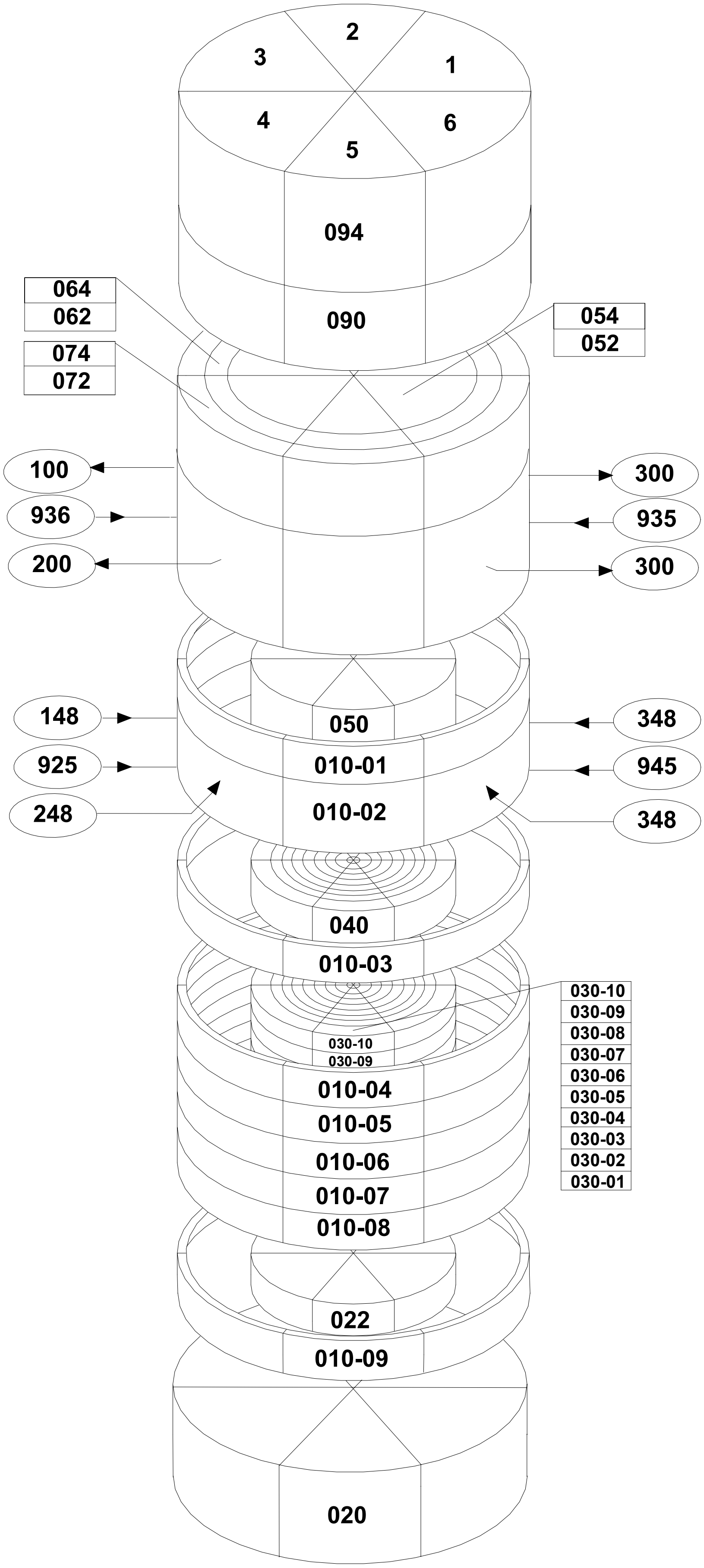

Fig.2. Zaporizhzhya NPP unit 5 RELAP5-3D reactor model nodalization.

Table 2. Zaporizhzhya NPP unit 5 design and RELAP5-3D calculated steady state parameters.

Parameter	Units	ZNPP unit 5 design data	RELAP5-3D calculated data
Reactor heat power	MW	3000±60	3000
Reactor neutron power	$\%N_{rated}$	100±2	100.0
Primary pressure (abs.) at core outlet	kgf/cm^2	160±2	160
SG pressure (abs.)	kgf/cm^2	64±2	63
MSH pressure (abs.)	kgf/cm^2	61±1	60
Reactor inlet coolant temperature	Deg. C	288±2	289.5
Average coolant temperature rise across the reactor core	Deg. C	30.8	30.5
Reactor coolant flow rate	m^3/hr	84800^{+4000}_{-4800}	83600
Pressure drop by reactor coolant system sections: Reactor (without nozzle) Core Steam generator MCP	kgf/cm^2	 3.88 1.45 1.35 6.33	 4.00 1.66 1.30 6.37
Pressurizer level	m	8.77±0.15	8.77
Water level in SG (measured by level meter with 4 m range)	m	2.10±0.05 (SG hot bottom) 2.25±0.05 (SG cold bottom)	2.19
Water level in SG (measured by level meter with 1 m range)	m	0.320±0.050	0.323
Steam flow rate from SG	t/hr	1470±60	1476

Kozloduy NPP unit 6 RELAP5-3D model

For the development of Kozloduy NPP unit 6 RELAP5-3D model the baseline RELAP5/Mod3.2 input deck, developed and validated by Bulgarian Institute for Nuclear Research and Nuclear Energy (INRNE), and cross-sections libraries, prepared by Pennsylvania State University (PSU) from the Kozloduy NPP VVER-1000 coupled code benchmark specification [7] were used. The RELAP5-3D model nodalization is shown in Fig.3.

A stable operational steady-state was obtained and the calculated plant conditions compared with the initial steady-state conditions for the Kozloduy NPP benchmark. Preliminary results for main technological parameters are shown in Table 3. It is necessary to note that correct enough predictions of relative change of hot and cold leg temperatures indicate that the RELAP5-3D model allows to reflect the correct coolant passing in reactor vessel. As it is known the research of coolant mixing in VVER-1000 reactor vessel has shown [8], that more than 50 % of coolant of cold leg arrives to the hot leg of same loop. A detailed RELAP5-3D Kozloduy NPP coupled code benchmark analysis including research of sensitivity to the reactor model nodalization is being planned in the nearest future.

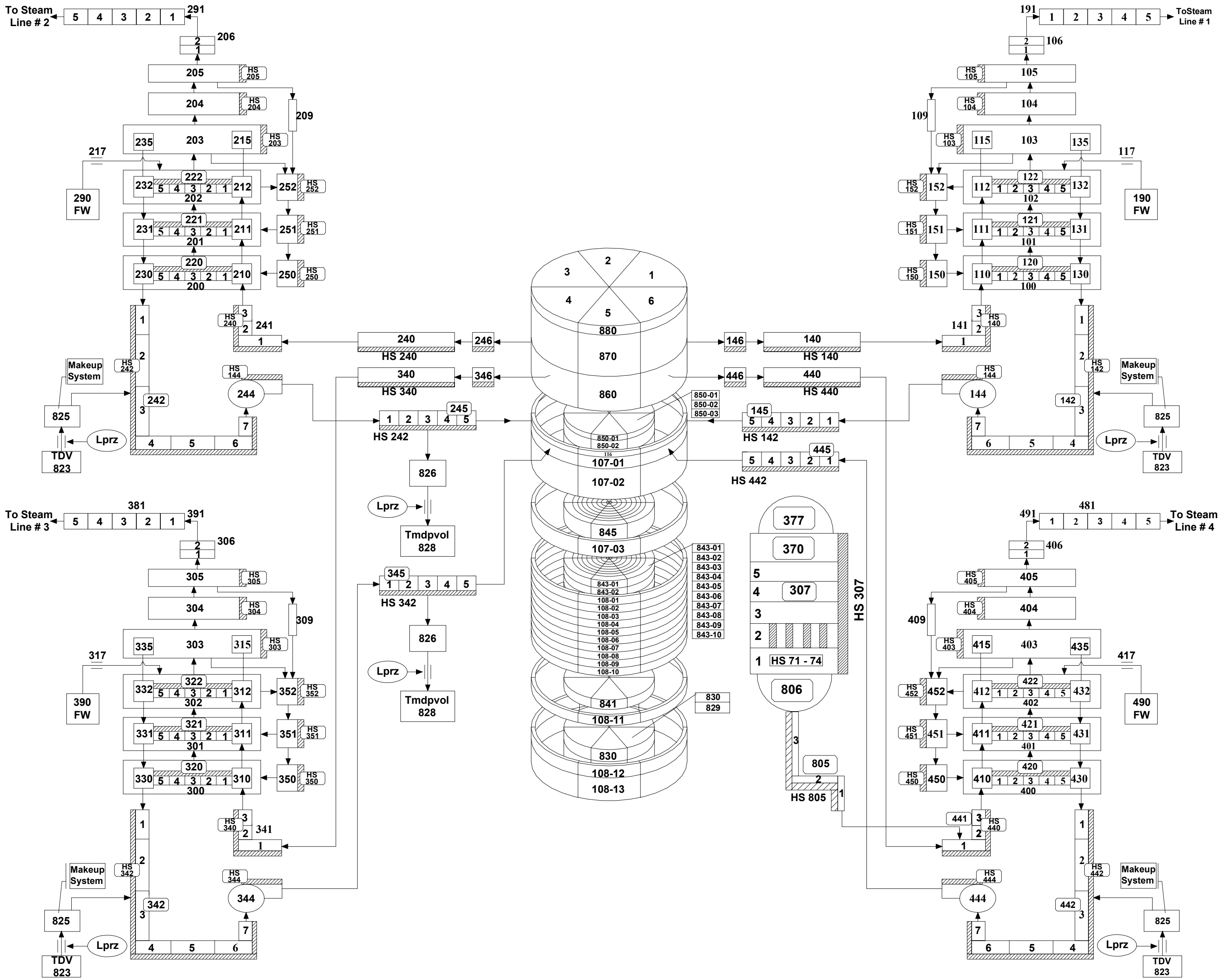

Fig.3. Kozloduy NPP unit 6 RELAP5-3D model nodalization.

Table 3. Main technological parameters for the Kozloduy NPP benchmark initial steady-state.

Parameter	Units	Kozloduy NPP benchmark specification [7]	RELAP5-3D calculated data
Reactor heat power	MW	883.50	883.50
Primary side pressure	MPa	15.6	15.6
RCS first cold leg temperature	°K	555.55	553.83
RCS second cold leg temperature	°K	554.55	552.91
RCS third cold leg temperature	°K	554.35	553.03
RCS fourth cold leg temperature	°K	555.25	553.55
RCS first hot leg temperature	°K	567.05	565.55
RCS second hot leg temperature	°K	562.85	562.69
RCS third hot leg temperature	°K	550.75	548.85
RCS fourth hot leg temperature	°K	566.15	564.69
First loop flow rate	kg/s	5031	5014.4
Second loop flow rate	kg/s	5069	5033.7
Third loop flow rate	kg/s	-1544	-1492.9
Fourth loop flow rate	kg/s	5075	5013.4
Pressurizer level	m	7.44	7.437
Water level in SG #1	m	2.30	2.419
Water level in SG #2	m	2.41	2.470
Water level in SG #3	m	2.49	2.471
Water level in SG #4	m	2.43	2.437
Secondary side pressure	MPa	5.937	5.957

Assessment of RELAP5-3D CHF Correlations

One of the most important issues of the In-Depth Safety Analysis is an accurate computation of the critical heat flux (CHF) in the reactor core. It is well known [3,9] that Groeneveld three-dimensional table model of the RELAP5/Mod3.2 code significantly overestimates the critical heat flux in VVER type assemblies at low pressure. RELAP5-3D code users may activate a new set of CHF correlations, which were developed by the Nuclear Research Institute in the Czech Republic [3]. These PG-CHF correlations are based on data in the Czech Republic data bank to be used for replacing the “CHF Table Look-up” method. The comparative assessment of PG-CHF correlations and “CHF Table Look-up” method using rod bundle critical heat flux data [10] from KS-1 experimental facility at the Russian Research Center “Kurchatov Institute” has been performed. Predictions of Bezrukov’s correlation [11], which has been implemented in Ukrainian ISA RELAP5/Mod3.2 models using a set of the control variables, also are estimated.

The updated KS-1 37-rod Bundle RELAP5/Mod3.2 model and 27 test points [10] were used for the comparative assessment of indicated CHF correlations. These test points cover all range of available experimental data (pressure, mass flux, inlet temperature). The results from the calculations are provided in Table 4. Considering a 10 % uncertainty in the measured CHF one can see that the PG-CHF correlation is the best. The mean deviation for PG-CHF correlation calculations is –3.2%, with a standard deviation of 6.6%. Also it is possible to conclude that Bezrukov’s correlation gives better results, than the Groeneveld model, though usaging this correlation is incorrect outside of the recommended limits of its applicability [11]. The mean deviation for Bezrukov’s correlation calculations is –16.3%, with a standard deviation of 12.4%. The mean deviation for Groeneveld model calculations is –27.6%, with a standard deviation of 13.5%.

The assessment of influence of RELAP5-3D code CHF correlations on result of the large-break loss-of-coolant accident analysis has been performed. For fast achievement of critical heat flux the scenario with loss-of-offsite-power and failure of all accumulators, high pressure and low pressure injection systems was assumed. The calculations were conducted with using of Zaporizhzhya NPP unit 5 ISA RELAP5/MOD3.2 model [6]. The calculated maximum cladding temperatures are shown in Fig.4. As expected the PG-CHF correlation demonstrates more conservative results than the Groeneveld model.

Table 4. The results of RELAP5-3D CHF calculations for the KS-1 37-rod bundle tests.

Point	Pressure, MPa	Mass flux, kg/m^{2}s	Inlet temperature (^{0}C)	Measured CHF, MW/m^2	Groeneveld model		Bezrukov's correlation		PG-CHF correlation	
					Calculated CHF, MW/m^2	Deviation, %	Calculated CHF, MW/m^2	Deviation, %	Calculated CHF, MW/m^2	Deviation, %
1	4.73	246	134	0.4920	0.5608	-14.0	0.5599	-13.8	0.5103	-3.7
2	4.76	698	137	0.9659	1.3418	-38.9	1.1338	-17.4	1.0631	-10.1
3	4.33	731	91	1.1003	1.4930	-35.7	1.2760	-16.0	1.2145	-10.4
4	4.23	398	64	0.7529	0.9685	-28.6	0.8928	-18.6	0.8461	-12.4
5	4.88	611	61	1.0901	1.3807	-26.7	1.1768	-7.9	1.1782	-8.0
6	3.00	719	122	0.9353	1.3497	-44.3	1.2483	-33.5	1.0203	-9.0
7	2.89	327	86	0.6052	0.7777	-28.5	0.8064	-33.2	0.6314	-4.3
8	2.84	1169	96	1.3801	1.9449	-40.9	1.7290	-25.3	1.4556	-5.5
9	2.77	1290	76	1.4603	2.1262	-45.6	1.8799	-28.7	1.6110	-10.3
10	3.71	656	137	0.9121	1.2630	-38.5	1.1232	-23.1	0.9720	-6.6
11	3.63	1580	140	1.5102	2.1132	-39.9	1.8475	-22.3	1.5993	-5.9
12	3.63	1159	161	1.1801	1.7406	-47.5	1.5056	-27.6	1.2757	-8.1
13	3.63	1489	161	1.3703	1.9580	-42.5	1.7290	-26.2	1.4581	-6.4
14	5.17	757	159	1.0202	1.3599	-33.3	1.1312	-10.9	1.0617	-4.1
15	4.76	1169	139	1.3601	1.8252	-34.2	1.5383	-13.1	1.4304	-5.2
16	4.65	1670	140	1.6403	2.1692	-32.2	1.8720	-14.1	1.7046	-3.9
17	4.57	1110	101	1.4100	1.9275	-36.7	1.6039	-13.8	1.5292	-8.5
18	5.21	240	172	0.4610	0.5108	-10.8	0.5042	-9.4	0.4624	-0.3
19	5.59	682	192	0.9392	1.1761	-25.2	0.9825	-4.6	0.9060	3.5
20	5.43	375	64	0.8280	0.9182	-10.9	0.8372	-1.1	0.8439	-1.9
21	5.72	580	96	1.0602	1.2447	-17.4	1.0577	0.24	1.0708	-1.0
22	5.95	690	113	1.1302	1.3697	-21.2	1.1411	-1.0	1.1514	-1.9
23	3.82	276	171	0.4790	0.5775	-20.6	0.6320	-31.9	0.4810	-0.4
24	5.75	288	190	0.5380	0.5822	-8.2	0.5492	-2.1	0.5083	5.5
25	5.75	252	208	0.4790	0.4938	-3.1	0.4801	-0.2	0.4356	9.0
26	5.76	271	260	0.4452	0.4589	-3.1	0.4464	-0.3	0.3802	14.6
27	3.79	271	236	0.4221	0.4867	-15.3	0.6129	-45.2	0.3841	9.0

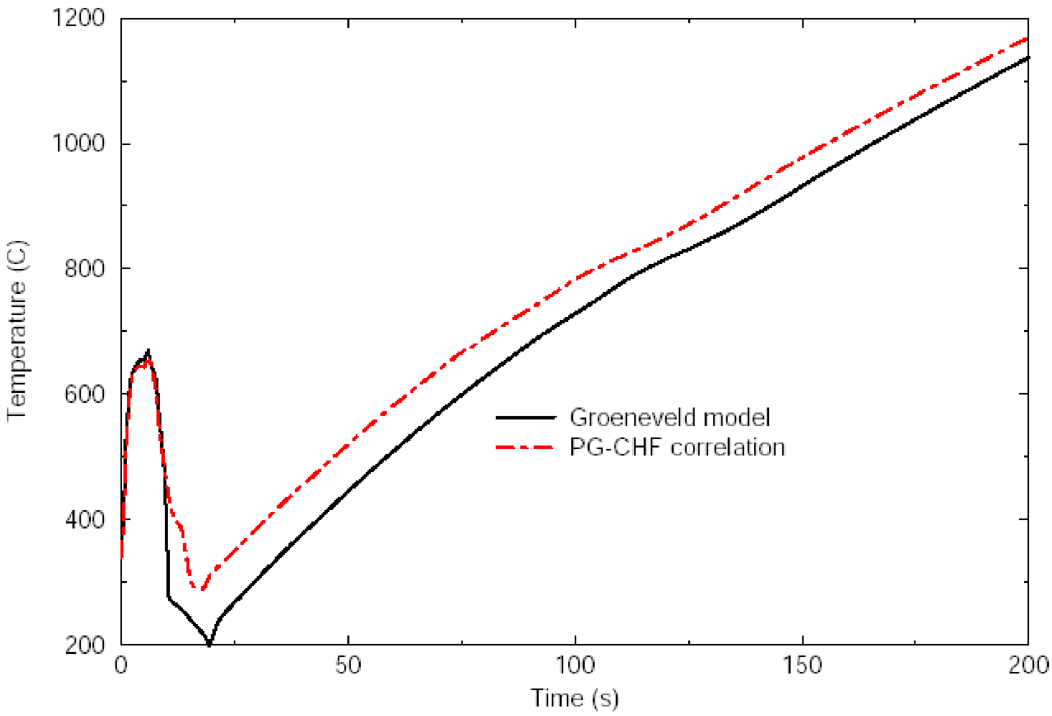

Fig.4. The calculated maximum clad temperatures for PG-CHF and Groeneveld correlations.

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