Analysis of the connection of an idle MCP with three operating without a preliminary reduction in the power of the VVER-1000 reactor

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Abstract. The paper analyzes the transient process caused by connecting an idle loop (turning on an idle main circulation pump (MCP)) without preliminary reduction in the power of a VVER-1000 reactor plant (RP) operating at a rated power corresponding to three MCPs. The process under consideration is included in the "Reactive accidents" section of materials for justifying the safety of VVER-1000. Modeling is carried out on the example of the 3rd power unit of the Kalinin NPP [1]. For the calculations, we used the improved evaluation code ATHLET [2], which is included in the AC² software package, officially obtained by the National Research Nuclear University MEPhI on the basis of a license agreement with Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Germany [3]. The ATHLET code has been certified in Russia for calculating stationary and transient conditions in water cooled reactors [4]. For the conservatism of the calculation, the study did not take into account the work of the PRL, APR, WP-1, WP-2 and AWP, the functioning of which is aimed at limiting the increase in the reactor power during the transient process. Blocking the signal to turn off the MCP on the fact of a decrease in the level in the SG and of the three ECCS systems, the operation of only one system is taken into account. For a number of reasons, this calculation was carried out for the end of the campaign. Implementation of design safety criteria for the adopted transition scenario is demonstrated.

1. Introduction

This mode is included in the section “Reactive accidents”. A feature of the reactor at power unit № 3 of the VVER-1000 (B-320) Kalinin NPP is the azimuthal uneven distribution of the cold and hot loops nozzles around the perimeter of the vessel. The angle between the fourth and first, and also between the second and third nozzles is 55 °, and between the first and second, and also between the third and fourth nozzles 125 °; the first pipe is located bottom left, the rest-clockwise (figure 1). For computational modeling was used, the thermal-hydraulic system code ATHLET (Analysis of Thermal-Hydraulics of Leaks and Transients), which developed at the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS GmbH) and was originally intended to analyze the entire spectrum of leakage and transient analyzes in PWR and BWR type LWR reactors. However, experience showed that the code can be successfully used to the Russian reactors of the VVER and RBMK type. Examples of this are works [5-9].
2. The design scheme of the simulated power plant

The elements of the design scheme of unit № 3 of the Kalinin NPP are shown in detail in figures 2 (nodalization diagram of the reactor core) and 3 (first loop with part of the reactor chamber). Some results of this calculation scheme are given in [10–15].

Let us consider in more detail the reactor model, which is described as follows:

- the standpipe area, the lowering section and the space between the bottom of the reactor and a perforated bottom sides of core shaft shell is modeled by six geometric figures, hydraulically connected in the transverse direction. Of these channels, four are connected directly to the cold loops-1st, 2nd, 3rd and 4th, and the other two are located between the 1st and 2nd and 3rd and 4th plots, respectively. Such a standard condition: azimuthally-uneven distribution of pipes of the VVER-1000 reactor of unit 3 and Kalinin NPP, as mentioned above;
- seven parallel sections in the subzone of the reactor between the perforated bottom of the shell and the lower support grid of the cassettes, with the exception of the support cups of the cassettes, hydraulically connected in the transverse direction. The geometric characteristics of these channels are height, volume, flow area, etc. are determined in accordance with the subsequent partition of the active zone into channels combining the corresponding fuel assembly FA groups;
- seven groups of parallel hydraulic sections (six peripheral and one central) in the reactor core. The geometric characteristics of each zone, as well as in the subzone space, are determined in accordance with the number of fuel assemblies in a particular group. In this case, 24 fuel assemblies are summarized in the peripheral channels, and 19 fuel assemblies in the central one. It is possible to take into account convective heat transfer between parallel adjacent generalized channels. Common to the channels of each group is only the pressure at the inlet and outlet. When calculating the point kinetics, a fuel assembly was selected which has 2 groups of fuel elements with different energy generation along the radius, also these 2 groups have 3 types each that differ in different energy generation in height. This model allows cassette modeling of the active zone. The calculation of energy is carried out through the use of specified energy sources in fuel assemblies. When calculating the three-dimensional energy release field in the core, each fuel assembly was divided in height into 12 parts. The first and twelfth sections were included in the zone of end reflectors, the sections from the second to the eleventh were in the heat-generating part of the cassette;
- System of steam lines from steam generator to turbine with safety valves, BRU-A, BRU-K, BZOK, BRU-SN, check valves (about 30 control volumes relative to each steam generator);
- Piping system, from the main feed water pumps, auxiliary and emergency pumps to the steam generator, including the system of control and shut-off valves (about 20 control volumes relative to one steam generator);
- The internal volume of the steam generator is modeled by 6 interconnected elements that allow, in turn, to model the separator, internal circulation. The scope of the stills of the steam generator modeled is the 7th volume in the vertical direction. A total of 16 control volumes are used to describe SG;
- All thermophysical objects, both on the first and on the second circuit are provided with thermal structures where they take place.
- The operation control of all necessary equipment elements, which are involved in the process, is modeled.
An additional control system is developed, which allows to set all the necessary parameters of the equipment operation (mass flow rate in loops, temperatures, pressure levels in the steam generators and pressure compensator, etc.) before the start of the transition process on the zero-transient.

Figure 1. Top left is a diagram of the connection of circulation loops with a reactor, bottom is a diagram of splitting of the core into seven groups of parallel hydraulic channels (six peripheral and one central) and the right diagram of the coolant flow in reactor of the Kalinin NPP unit 3.
Figure 2. Nodalization diagram of the reactor core.

Figure 3. Nodalization diagram of the reactor objects along the primary circuit, related to one of the circulation loops.

3. Description of the process (Accident Scenario)
The results of the calculation of the transient mode (connecting MCP No. 1 with three other MCPs operating) are presented in figures 4-12. Table 1 shows the chronology of the main events, table 2 shows
the fulfillment of the design criteria for assessing safety, and table 3 shows the extreme values of the main equipment during the entire process. All data are reflected taking into account the error and inertia of the measured parameters.

The transient process associated with the connection of an idle loop with three working MCPs out of four without preliminary reduction in power to 30% of the nominal according to the technological regulations for the safe operation of the power unit. The value of the thermal power of the reactor before the transition process is 67% of the nominal value. For a number of reasons, this calculation was performed at the end of the campaign. This period is characterized by the maximum value of the temperature of repeated criticality and the maximum, in absolute value, negative values of the reactivity coefficients with respect to the temperature of the fuel and coolant. By the end of the campaign, the coefficient of reactivity in coolant temperature, while remaining negative, increases in absolute value by almost 100%, and the coefficient of reactivity in fuel temperature increases in absolute value (negative in value) by about 10%, which increases the conservatism of the process under consideration compared to other periods of the campaign.

It is assumed that the following systems do not work: PRL, APR, WP-1, WP-2, AWP, and out of the three ECCS systems, only one system is taken into account.

In the closed state, in loop №1, with the MCP turned off, there is a reverse run of the coolant. Coolant begins to move from cold to hot side of loop. As a result of this process, the temperature in the hot nozzle becomes lower than in the cold. This leads to the fact that the coolant of the disconnected loop, which reduces the temperature at loops No. 2 and No. 4, enters the outlet chamber of the reactor with hot coolant. In this case, less influence is exerted on loop №3 due to the fact that this loop is farthest from the loop №1. This effect can be more accurately shed on the graphs of the change in the temperature of the coolant in the loops.

After connecting loop №1, the coolant temperature changes in hot and cold loops. A rapid increase in the temperature of the coolant at the inlet to the reactor (figure 5) and an increase in density (the slowing-down property of the coolant improves) leads to an increase in the reactivity coefficient for the coolant temperature, as a result of which an abrupt increase in power from 67% to 85% (figures 4). A further increase in the temperature of the coolant at the inlet to the reactor reduces the power of the reactor and stabilizes the process (the reactivity coefficient for the temperature of the coolant has been exhausted).

An increase in the temperature of the coolant at the outlet of the reactor increases the power of the steam generator and the flow rate of steam through the steam collector. As a result, the steam level will increase, this can be seen from the indication of the “small” level gauge (figures 7). A signal is issued to turn off the MCP, which is blocked according to the scenario. Two turbo feed pumps shut off. The change in steam flow led to the closure of the stop valves and to a further shutdown of the turbine. After that, the power of the installation increases, until the first EP signal is triggered (figure 12), which is skipped. So, as the process is analyzed on the principle of EP diversion (emergency protection is triggered by a second signal, the first signal is skipped). To compensate for boiler water in the steam generator, auxiliary electric pumps (AEP) are connected (figure 9). The increase of pressure in the second circuit to the triggering of the BRU-A and BRU-K systems (figure 8). However, a further increase in power led to a decrease in the total weighted water level (-650 mm) (figure 6) in the steam generator until the signal for triggering the second EP signal (figure 12). After which the CPS (control and protection system) began to sink into the active zone. To replenish feed water, water from emergency feed electric pumps enters to the steam generator (figure 9).

The pressure in the primary circuit is normalized as a result of the triggering of the pressure maintenance system in the primary circuit. It is important to emphasize that only normal operation systems that worked in the normal mode worked.

The transition process affected the change in the following parameters: increase in the temperature of the shell, fuel and a decrease in the stock before the crisis (figures 10 and 11 respectively). The fuel temperature increased by 15% from the initial one, that is, from 981 °C to 1130 °C. Despite the increase in flow through the reactor, the maximum linear load of the hot fuel rod was 431 W/cm. The whole
calculation lasted 4800 seconds, a stationary process (0-3000 sec), a transient process (3000-4800 sec). In the illustrations shown, the stationary process was skipped, part of it was demonstrated at the beginning of the transient processes.

Table 1. Chronology of main events.

| Time, s          | Event                                                                 | Event reason                                                                 |
|------------------|-----------------------------------------------------------------------|------------------------------------------------------------------------------|
| 0.000000E+00    | Start of the process connecting all 4 pumps                            | Requirement of condition                                                     |
| 1.200000E+03    | Shutdown of MCP №1                                                     | Requirement of condition                                                     |
| 3.000000E+03    | First loop connection                                                  | Requirement of condition                                                     |
| 3.020052E+03    | Achieving maximum plant power Signal for turning off the MCP №1        | Deviation of the level of the small level gauge from the nominal value in the steam generator №1 by more than 300 mm. By condition skipped |
| 3.029665E+03    | Start closing turbine stop valves                                      | Turbine shutdown due to level increase, start of shutting off turbine stop valves |
| 3.029665E+03    | Turbo pump shutdown 1                                                  | shutdown of the turbine and pressure in the MSH> 5.5 MPa                    |
| 3.029665E+03    | Turbo pump shutdown 2                                                  | shutdown of the turbine and pressure in the MSH> 5.5 MPa                    |
| 3.029665E+03    | Operation of the 1st signal for EP                                     | The power of the reactor exceeds the maximum possible, with the turbo pumps turned off. By condition skipped. |
| 3.080601E+03    | Operation of the 2nd signal for EP                                     | Deviation of the total weight level of water by more than 650 mm in SG №1   |
| 3.084781E+03    | Signal on the movement of the CPS EP                                   | Delay taking into account the formation of the signal and its passage in the electronic system |
| 4.800000E+03    | Process end                                                            |                                                                              |

Table 2. Fulfillment of design criteria for safety assessment.

| Safety Assessment Criteria                                                                 | Value achieved |
|-------------------------------------------------------------------------------------------|----------------|
| a) fuel pellets do not melt even locally (fuel temperature is assumed to be 2540 °C for “burned out” fuel and 2840 °C for “fresh” fuel; | 1130 °C        |
| b) the maximum pressure of the primary circuit should not exceed 110% of the calculated, that is, 19.4 MPa; | 17.11 MPa      |
| c) the maximum pressure of the second circuit should not exceed 110% of the calculated, that is, 8.6 MPa; | 7.32 MPa       |
| d) the average radial enthalpy of fuel does not exceed 830 J/g for burned fuel and 963 J/g for "fresh" fuel | 392.3 J/g      |
### Table 3. Extreme values of the main parameters.

| Parameter                                                                 | Maximum value | Minimum value |
|---------------------------------------------------------------------------|---------------|---------------|
| **Total reactor power (W)**                                               | 2.526281E+09 / 3.020052E+03 |               |
| **The relative power of the reactor**                                     | 8.420937E-01 / 3.020052E+03 |               |
| **The position of the CPS working group over the core (cm)**              |               |               |
| 10 group                                                                  |               |               |
| Maximum value                | 8.710000E-01 / 0.000000E+00 |               |
| Minimum value                | 5.000000E-00 / 3.088451E+03 |               |
| 1,2,3,4,5,6,7,8,9 groups                                                 |               |               |
| Maximum value                | 1.044900E+02 / 0.000000E+00 |               |
| Minimum value                | 5.000000E-00 / 3.088451E+03 |               |
| **The linear power of the fuel rod, (W/cm)**                             |               |               |
| Maximum value                | 4.301779E+02 / 3.028650E+03 |               |
| Minimum value                | 2.748821E+02 / 0.000000E+00 |               |
| **Fuel temperature, (°C)**                                               |               |               |
| Maximum value                | 1.128229E+03 / 8 / 3.022201E+03 |               |
| Minimum value                | 2.788401E+02 / 1 / 0.000000E+00 |               |
| **Shell temperature, (°C)**                                              |               |               |
| Maximum value                | 3.473876E+02 / 8 / 2.950885E+03 |               |
| Minimum value                | 2.788434E+02 / 1 / 1.587346E+00 |               |
| **Stock before the crisis**                                               |               |               |
| Minimum value /section/time     | 3.541884E+00 / 8 / 3.030679E+03 |               |
| **Enthalpy of fuel, (J/g)**                                              |               |               |
| Maximum value                | 392.3 / 8 / 3.022201E+03 |               |
| Minimum value                | 98.04 / 1 / 0.000000E+00 |               |
| **Temperature of coolant, 1st loop (°C)**                               |               |               |
| Maximum value                | 2.972486E+02 / 3.042937E+03 |               |
| Minimum value                | 2.788000E+02 / 0.000000E+00 |               |
| **Pressure in the steam generator №1**                                   |               |               |
| Maximum value                | 7.349640E+06 / 3.036738E+03 |               |
| Minimum value                | 5.979626E+06 / 6.074298E+01 |               |
| **Pressure in the steam generator №2**                                   |               |               |
| Maximum value                | 7.320110E+06 / 3.036738E+03 |               |
| Minimum value                | 5.979271E+06 / 6.074298E+01 |               |
| **Pressure in the steam generator №3**                                   |               |               |
| Maximum value                | 7.311341E+06 / 3.036738E+03 |               |
| Minimum value                | 5.979196E+06 / 6.074298E+01 |               |
| **Pressure in the steam generator №4**                                   |               |               |
| Maximum value                | 7.336069E+06 / 3.036738E+03 |               |
| Minimum value                | 5.979157E+06 / 6.074298E+01 |               |
Figure 4. Power of reactor.

Figure 5. The temperature of the coolant at the outlet of the cold leg (entrance to the reactor): 1-1st loop, 2-2nd loop, 3-3rd loop and 4-4th loop.
Figure 6. Change in total weight level: 1-1-st steam generator, 2-2-nd steam generator, 3-3-th steam generator and 4-4-th steam generator.

Figure 7. Level change on the "small" level gauge: 1-1-st steam generator, 2-2-nd steam generator, 3-3-th steam generator and 4-4-th steam generator.
Figure 8. Consumption through BRU-A and BRUK: 1-BRU-A for the 1st steam generator, 2-BRU-A for the 2nd steam generator, 3-BRU-A for the 3rd steam generator, 4-BRU-A for the 4th steam generator and 5-flow through BRU-K.

Figure 9. Feedwater flow rate: 1- Auxiliary water flow rate and 2-Emergency feedwater flow rate.
**Figure 10.** Fuel temperature along the height of the hot fuel rod of the hot cartridge (uniform partition along the height).

**Figure 11.** Shell temperature along the height of the hot fuel rod of the hot cassette (uniform partition along the height).
Figure 12. EP signals: 1 - the first EP signal upon an increase in the power of the nuclear power plant from the installed one, 2 - the second EP signal upon the fact of a decrease in the level of feed water in the steam generator.

4. Conclusion
The “reactive accident” was analyzed with the idle loop connected without preliminary reduction of power to 30% using the example of power unit №. 3 of the Kalinin NPP. This work fully demonstrated the reaction of the system and the process of similar transients in the first and second circuit. Such work shows the reverse “reaction” of the main equipment in such emergency situations. Due to this, you can evaluate the readiness of the system and personnel in similar cases and also in the presence of weaknesses to prevent them during the design, construction or installation of equipment. The calculation showed the need to upgrade the algorithms of the power supply unit of steam generators when introducing a connection mode for an idle loop without first reducing the power. For the entire billing period, none of the safety criteria was exceeded. The performed calculations show that in the considered modes, a sufficient margin is maintained until the heat transfer crisis and fuel element damage does not occur.

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