

Using the unit software model to improve design solutions and optimize process management*

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Abstract

Advanced design power units are distinguished by a high degree of digital transformation. Therefore, of particular interest are operator information (intelligent) support systems, which can reduce the workload on operating personnel as well as predict possible deviations long before they evolve into severe emergencies.

The article analyzes the current standard process documentation that requires solutions to support the operator and determines the list of system functions that should be provided to improve the safety level of nuclear power plants. A brief overview of the world experience in implementing such solutions is also provided.

As an example of the further development of operator support systems, the authors consider the operator information support system (OISS), which is being developed at the NvNPP pilot unit with the VVER-1200 reactor. The OISS functions will make it possible to fulfill the requirements of standard process documentation that are currently not implemented in the power unit design.

The key features of the OISS under development are step-by-step interactive procedures and the unit software model. The authors provide a brief description of the power unit software model and consider several examples of its practical application as part of the OISS to improve design solutions and optimize automatic process control. In the years ahead, it is proposed to implement the OISS at power units under construction in order to reduce the information overload of operators and create conditions for a step-by-step increase in the automation level of the power unit control.

Keywords

OISS, technological process, interactive procedure, power unit software model, decision making, monitoring, design solutions, optimization, APCS, algorithms

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Introduction

In accordance with the Nuclear Safety Regulations for NPP Reactors (NP-082-07 2007), the operator information support system (OISS) must be implemented as part of the normal operation control systems and safety control systems. A similar requirement is given in Clause 3.4.1.1., (NP-001-15 2015). According to Clause 3.4.5.1., NP-001-15, the OISS should provide the control room personnel with generalized information about the NPP parameters characterizing the state of the safety functions.

The comments to NP-001-15 (RB-152-18 2018) indicate that the requirement of Clause 3.4.5.1 sets the NPP project developer the task of finding such a method for generalizing information on the current NPP safety state that would allow the operator to minimize the number of generalized parameters to quickly assess the situation at the NPP unit and make a decision.

The requirements for the operator information support are more fully set out in GOST R IEC 60964-2012. Nuclear power plants. Control Rooms. Design. (GOST R IEC 60964-2012 2014) Cl. 3.21. Operator support system: “A system or systems designed to support abstract thinking tasks or intellectual information processing tasks performed by control room personnel.” Clause 7.7.2.5 defines the operator support functions that should be provided to improve the NPP safety, operability and performance as follows:

- displaying safety parameters and control of safety functions (IEA 60960-1988 2000);
- diagnosing the NPP;
- advising the operator during normal operation and post-accident situations, for example, based on symptom-based procedures; and
- exerting automatic control over energy modes.

Using the power unit software model, it is possible to diagnose the NPP state when developing guidelines for managing beyond-design-basis events (including severe accidents).

As far as possible, the functions should be integrated into the overall control room design.

Information support

At the Biblis NPP in Germany in the 1980s, the STAR abnormal situation analysis system was introduced (Butner 1985). It uses models of deviations from normal operation. The SPRINT system was introduced at the Kalinin and Novovoronezh NPPs (Anokhin et al. 2016). SPRINT is a real-time decision support system for diagnostics of nuclear power plants using intelligent search mechanisms.

As part of the R&D implementation plan of Rosenergoatom Concern JSC, the requirements and basic solutions for the creation of an operator’s intellectual (information) support system (OISS) are being developed.

The interested organizations have agreed on the following list of functions of the OISS:

- determining the power unit mode (level of defense in depth) and state;
- calculating alarm settings depending on the current state of the power unit;
- exerting control over operational limits and conditions as well as limits and conditions of safe operation;
- monitoring the state of the power unit permanent equipment;
- monitoring security systems;
- exerting control over automatic equipment control;
- forecasting the main technological process using the power unit software model;
- providing operational personnel with interactive instructions on the power unit startup/shutdown procedures, equipment commissioning/decommissioning, routine checks, trials and tests, interactive analogs of the current Normal Operation Failure Procedures, Emergency Operating Procedures, Beyond Design Basis Accidents Management Guidelines, Severe Accident Management Guidelines;
- generating operational logs on an automatic basis;
- providing the operator with reference information about possible causes of signaling on the MCRs (ECRs) (reaction to the signal); and
- providing recommendations for technological process control optimization.

The functions of the OISS ensure the fulfillment of the operator support requirements set in (GOST R IEC 60964-2012 2014), which are currently not implemented in the automated process control system (APCS) of NvN-PP-II-1, including the intelligent information processing requirement in order to unload the control room operating personnel in all power unit operating modes.

Innovative Company SNIIPATOM JSC has developed a model of the operator information support system (MOISS), which includes a power unit software model and interactive applications that can be divided into logic units. The first version of the model has been functioning at NvNPP-II-1 from the date of startup.

The unit of interactive procedures contains applications designed to control the safe performance of work and support the operator in the step-by-step execution of unit startup/shutdown programs and standard switch cards. This tool cuts the time for processing information and reduces the likelihood of possible human errors and failures.

An example of interactive procedures is the unit startup procedure, which contains active links to operational documentation and has the ability to display the values of process protections and interlocks of equipment, control time delays for various operating modes of the power unit. Validation of interactive procedures in 2019 at NVNPP-II-1 confirmed that the procedures meet the requirements for them and are convenient for use by the MCR operating personnel.

The unit of interactive action charts (IACs) includes applications for analyzing the process behavior that reduce the load on the operator in situations with limited decision time. The IACs are designed for personnel to perform a number of sequential actions, when a process alarm is triggered on the MCRs, aimed at bringing the parameters and equipment to a state in which they do not exceed the operational limits and/or conditions of safe operation. The charts contain descriptions of possible causes of alarms and the operator's actions to eliminate them. This unit was implemented in MOISS in accordance with (GOST R IEC 62241-2012 2014).

Intelligent support

The division into intelligent and information operator support (Anokhin et al. 2016) is very conditional, but it is indisputable that the intelligent component is based on mathematical and software models of the power unit.

Work on the creation of simulation models of complex thermal power facilities was carried out at the Institute for Problems in Machine-Building (IPMash) of the National Academy of Sciences of Ukraine, where simulation models of condensing steam turbine plants for thermal power plants and nuclear power plants were developed (Palagin and Efimov 1986).

The model of an NPP power unit with VVER-1000 includes mathematical and software models as well as simulation modeling (Lavrentichev and Tverskoy 2015). These developments can be used to synthesize new structures of local automatic control systems (Zhuravkin and Lebedev 2011). The power unit mathematical models are also used for testing the algorithms of NPP control systems and for verifying NPP training models (Zhuravkin et al. 2010; Kothe Doug 2011).

In 2010, the US Department of Energy established the Consortium for Advanced Simulation of Light Water Reactors (CASL). Its goal is to develop advanced computational models of light water reactors (LWRs) that can be used by utilities, fuel vendors, universities, and national laboratories to help improve the performance of existing and future nuclear reactors (Larzelere 2020 (accessed Jul 05, 2020)).

Similar work is being carried out for Generation IV reactors under the Nuclear Energy Advanced Modeling and Simulation (NEAMS) Program (Larzelere 2020 (accessed Jul 05, 2020)).

The Russian hardware/software package, “Virtual-digital NPP with VVER”, (Arkadov et al. 2014) has shown the fundamental possibility of creating in a common software environment a unified system of computational codes for interrelated calculations of various physical phenomena at NPP-2006. This complex is used to substantiate the safety of NPPs.

It is obvious that the operator's decision support system (“Recommendations for optimizing technological process control”) is an intellectual component of the OISS, which

is based on a power unit model that makes it possible to forecast various operating modes.

The main distinctive feature of the power unit software model used in the MOISS is that it was developed specifically for use in the APCS. Therefore,

- the software of the model is developed in accordance with the software development requirements for safety-related systems (Class 3, Category C, according to IEC 61226);
- the process is simulated an order of magnitude faster than the principal process of the power unit in normal operation and normal operation failure modes;
- the model works steadily during the fuel campaign in any normal operation and normal operation failure modes;
- the model is capable of starting at any moment of the campaign, in the state of the power unit determined by the sensor readings received from the UULS;
- the model has a convenient user interface;
- the model is focused on obtaining not a conservative but the most reliable estimate; and
- the model has been validated on a representative set of VVER-1200 operational data.

At the same time, the MOISS uses not simplified models typical for training simulators but a neutronic code of increased accuracy. Calculations of the core power distribution are performed using the SVC program certified by Rostekhnadzor, which is based on a direct solution of the neutron transport equation and does not use, in contrast to training programs, the homogenization of computational cells and the diffusion approximation.

A detailed thermohydraulic model of the core (163×16 design elements) is characterized by the following features:

- the number of parallel channels is equal to the number of fuel assemblies;
- the detail of calculations of the power density is determined by a specified arbitrary number of sections along the core height; and
- transverse leakages between the fuel assemblies are taken into account throughout the entire core height.

High discretization of the calculation model of the core makes it possible to obtain a detailed three-dimensional field of thermohydraulic parameters throughout the core, i.e., to estimate more accurately the critical power ratio indicators and the thermomechanical operating conditions of the fuel elements in each fuel assembly.

The transverse leakages in the core should be taken into account in the case of using jacketless fuel assemblies, in order to assess the redistribution of flow rates across the core section, which occurs due to uneven power density, as well as in the case of using mixed fuel loads consisting of fuel assemblies with different hydraulic characteristics.

The thermohydraulic model is based on the solution of a system of fundamental conservation equations and clo-

sing relations. The system of main equations describing the processes of heat and mass transfer in the primary and secondary circuits of the power unit includes the continuity equation, momentum conservation equation (Navier-Stokes equation), energy conservation equation and state equations written for each phase. In addition to the basic equations, an insoluble impurity-transport equation is written to simulate the boron absorber transfer in the primary reactor coolant circuit.

Due to the fact that the equations to be solved are non-stationary, the resulting solution is a set of states of the system under consideration for different time slices to an arbitrary forecasting depth from a given initial state.

The system of basic equations after discretization is solved using numerical methods. Discretization implies splitting the elements of the calculation scheme into separate nodes and links.

The power unit thermohydraulic model is created from a set of computational schemes, which are sets of interconnected equipment elements. Calculation schemes may include

- equipment (pumping units, electric heaters, tanks with interface levels);
- pipes, mixing chambers, turbine stages;
- hydraulic connections between individual components;
- heat exchanger tubes; and
- shutoff and control valves, check valves.

The software model is linked to the UULS signals, which makes it possible to initiate the simulation process from any current state of the power unit. The performance of the model is provided at the level of real time (or significantly higher). To make a forecast, it is possible to use the state of the power unit at an arbitrary moment in the past as an initial one with an accuracy of one second, while the entire operation history of the unit is archived. Using the over relaxation method, one can find a numerical solution to the system of equations describing thermohydraulic processes in an iterative manner, while the rate of convergence of the numerical solution makes it possible to achieve the required accuracy in a smaller number of iterations. Calculating the power unit parameters at a speed exceeding real time, even when models with high detail are used, is a prerequisite for the function of dynamic monitoring of the state of the power unit based on the comparison of the calculated data with the current sensor readings.

The APCS model is implemented on the basis of a separate software module that calculates the operating logic of model monitoring and control schemes. A set of calculation schemes is formed for it using the scheme editor, which is an integral part of the KRUIZ software environment. Sets of jointly compiled schemes reproduce the operating algorithms of the power unit main controllers as well as process protections and interlocks. Calculation schemes are formed on the basis of GET diagrams of typical software and hardware as well as the power unit

APCS technical design and the RP general designer' documentation. Therefore, the APCS model as a whole repeats the logic laid down in the APCS of the power unit. It is important to note that the operating algorithms for the unit controllers and process protections and interlocks are verified in the unit software model according to the results of the commissioning stage. In the same way, various technological systems and equipment of the secondary circuit, as well as auxiliary systems of the power unit, are simulated in detail.

As part of the OISS, the unit software model should be used to solve such problems as

- exerting validity control over the sensor readings received from the energy storage system (ESS) and security system (SS) by analyzing the mutual correspondence of the readings;
- diagnosing malfunctions in the main equipment;
- forecasting the development of the process from the current state forward for 15–30 minutes with the issuance of a warning signal about the exit of the monitored parameters beyond the operational limits in the absence of operator's control actions in a given time interval (automatic forecast); and
- forecasting the development of the process, taking into account operator's planned control actions in a given time interval (forecast at operator's request).

The description of the sequence of operator's control actions during forecasting at request (forecast scenario) is formed by the operator step by step as the calculation is performed. For standard sequences of actions, a prearranged scenario can be used. During forecasting, normal operation processes are simulated, including the unit startup from a cold state to operation at nominal parameters, unloading and shutdown, maneuvering power, as well as processes in the case of normal operation failure, including those accompanied by the fire protection activation and the unit accelerated unloading.

In addition to information support, the unit software model can be used to solve the following tasks:

- optimizing the process protections and interlocks and methods of unloading the reactor in order to increase the dynamic stability of new generation power units with V392M reactor plants; and
- carrying out variants calculations to improve circuitry and select the optimal composition and characteristics of heat exchange equipment.

Examples of practical application

Example 1. Increasing the power unit dynamic stability.

An example of using the unit software model for adjusting the process protections and interlocks and time delays is the numerical simulation of transient processes during experiments at NvNPP-II-1 when one feed elec-

tric pump (FEP) is switched off and the standby pump is not switched on. The level controllers in SG-1-4 (SG LC) switch to “stand-by” mode when the flow rate at the head of any FEP increases over 2000 m³/h. At the same time, they cover themselves, keeping the maximum feed water flow through the FEP in the range of 2000 m³/h. Stand-by mode is removed when the level in the SG is restored to the nominal value. The unit software model was used to simulate the change in the main parameters (Fig. 1) in the transient process caused by the fact that one FEP was switched off and the standby pump was not switched on at a power of 100% N_{nom} .

Before FEP-1 was switched off, the total flow rate at the feed water head was 7422 m³/h. The flow rate on the switched off FEP decreased to zero in seven seconds. The flow rates of FEP-2, 3, 4 increased up to 1953–2050 m³/h at each FEP, and the steady-state flow time of at least 2050 m³/h at FEP-3 exceeded the setting of 90 s. As the power of the reactor plant decreased, the flow rates at the head of each FEP stabilized at the level of 1700 m³/h. At the 220th second, after the level in SG-3 had increased to the nominal value, the SG level controllers switched to level maintenance mode. The FEP head pressure did not drop below 8.18 MPa. Based on the operation of the unit software model, it was concluded that the delay time to switch off should be increased to 300 s the operating FEPs according to the flow rate and pressure at their heads. The results obtained by JSC VNIAES, due to which it became possible to change the algorithms and successfully carry out dynamic tests.

One of the effective ways of improving the stability and ensuring the “survivability” of the NPP power unit is to develop methods for unloading the reactor when the main equipment of the primary and secondary circuits is shut down.

To analyze the unit dynamic stability, the conditions associated with switching off the FEP and the condensate electric pump (CEP) were simulated.

If one of the operating FEP is switched off and the standby one is not switched on, at 100% power, it is possible to fundamentally change the reactor unloading, replacing the operation of the power limiting controller (PLC) with the activation of the accelerated preventive protection (APP). When the APP is activated, the imbalance between the reactor power and the feed water consumption is eliminated almost immediately, and the power unit main controllers, including the feed unit of steam generators (SG), modify the secondary disturbances from switching off the FEP and triggering the APP.

An almost similar process occurs when the CEP is switched off, while a long-term imbalance remains between the reactor power and the secondary circuit power, which is determined by the condensate flow into the deaerator.

By simulating transient processes during shutdown of various types of equipment, it will be possible to make optimal decisions on changing the ways of unloading the unit as well as adjusting the settings for the process protections and interlocks and time delays for shutting down the equipment.

Example 2. Independent verification of algorithms for functional group control.

As part of the commissioning of the systems and equipment of the startup complex of NvNPP-II-1, -2, autonomous adjustment of the functional group control (FGC) was carried out. For a number of technological and logical reasons, the complex adjustment was partial.

In “forecast” mode, the power unit model can be used for performing the initial check and adjustment of the design FGC algorithms or developing new ones as a result of their approbation. To put the FGC into operation, it is necessary to check the operability of the design control and signaling algorithms in the interaction of technological equipment. It is also required to update the settings of thresholds of technological parameters, time characteristics of processes, FGC algorithms and corresponding

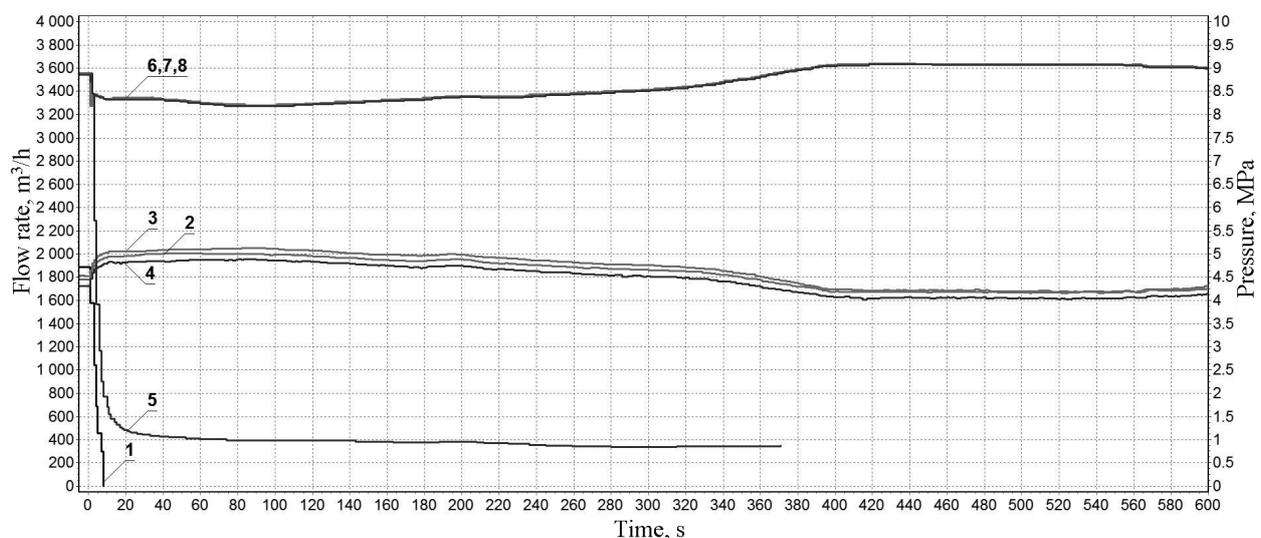


Figure 1. Flow rates and pressures at the FEP head in the transient process when one FEP is off and the standby one is not on (1, 2, 3, 4 are the flow rates of FEP-1, 2, 3, 4; 5, 6, 7, 8 are the pressures at the head of FEP-1, 2, 3, 4).

changes in GET projects. These possibilities are provided by the unit software model.

In the future, the software tools tested as part of the OISS and during the FGC validation will allow the transition from functional group control of individual subsystems (lower level FGC) in the sequence described below to functional group control of the power unit in complex normal operation modes, such as the power unit startup/shutdown (upper level FGC).

Stage 1. Before each startup of the unit, based on the algorithms and implemented interactive step-by-step procedures, a description of the expected sequence of operator's control actions (draft control scenario) is automatically generated. The operator is provided with the results of the forecast of the process advancement calculated by the power unit model with the possibility of correction. After the operator's confirmation, the draft scenario becomes a scenario according to which

- a forecast is periodically executed, the results of which are provided to the operator;
- deviations of the real process from the forecasted one are controlled;
- based on the control scenario and deviations of the real process from the forecasted one, recommendations are formed for the operator regarding control;
- in interactive step-by-step procedures, at each step, the readiness of the equipment for the next control action is automatically analyzed, information about the readiness is provided to the operator; and
- control is carried out by the operator remotely from the UULS video frames.

Stage 2. At each step of the interactive procedure, after automatic determination of the readiness for a control action, the operator allows this action.

Stage 3. For individual steps and/or groups of steps, the right to control is delegated to the program with a delay before issuing a timeout control command, during which the operator can block the command. The operator still has the opportunity to completely stop the FGC program. With the accumulated experience and trust in automation, the number of automatically performed steps will increase, and timeouts may decrease.

Example 3. During the operation of the turbine building nonessential services cooling water system at NvN-PP-II-1, the problem of increased temperature of the cooling water (more than 31 °C) was revealed annually from May to September, which leads to accelerated contamination of heat exchange surfaces and outlet pipes of small diameter (DN32 and less) with carbonate deposits. To ensure the required temperature regime of technological systems and fulfill the plan for generating electrical power, it is necessary to include standby equipment in parallel operation, which increases the risk of deviations in

the unit operation or leads to the need for an unplanned reduction in the electrical load when it is shut down. The temperature of the cooling tower makeup water during the hottest period of the year does not exceed 25 °C. It is proposed to install an additional pipeline to supply makeup water with a flow rate of up to 1000 m³/h directly to the suction of two service water pumps (SWP), which will reduce the cooling water temperature due to mixing. Using the software model, it became possible to calculate the change in the parameters of the cooling water after an additional pipeline was installed.

The following parameters were set for the calculation:

- consumption of cooling water to the turbine hall services = 4800 m³/h;
- cooling water temperature = 32.5 °C;
- make-up water temperature = 21.0 °C; and
- make-up water pressure = 0.105 MPa (g).

The results of calculating the maximum throughput of pipelines of various diameters and the corresponding de-

Table 1. Maximum throughput of pipelines of various diameter and the corresponding decrease in water temperature

Pipe diameter	Maximum flow rate, m ³ /h	Water temperature at the pump head, °C
DN200	286	31.4
DN300	783	30.3
DN400	1578	28.4
DN500	2701	25.8

crease in water temperature are given in Table 1.

Installing an additional external 500 mm diameter makeup water pipeline to the SWP suction will provide an acceptable temperature of the cooling water for the turbine hall nonessential services during the period of peak temperature loads.

Example 4. As a result of testing the SG blowdown operating modes, a low efficiency of the regenerative heat exchanger (RHE) of the SG was revealed (Arkadov et al. 2014). The temperature of the medium to be cooled in the RHE is 150–190 °C at a blowdown water flow rate of 60–80 t/h. The design temperature behind the RHE is no more than 100 °C. The SG blowdown temperature is reduced to 57 °C due to the blowdown water aftercooler.

The operation of the SG RHE is simulated using the unit software model. The most probable reasons for the RHE inefficiency were identified as follows:

- low flow rate of the coolant (0.63 and 0.34 m/s in the pipe and annular space);
- design error in connecting the RTO to the circuit for both flows. After the calculation was carried out using the unit software model at NvNPP-II-2, the RHE piping was reconstructed (Fig. 2).

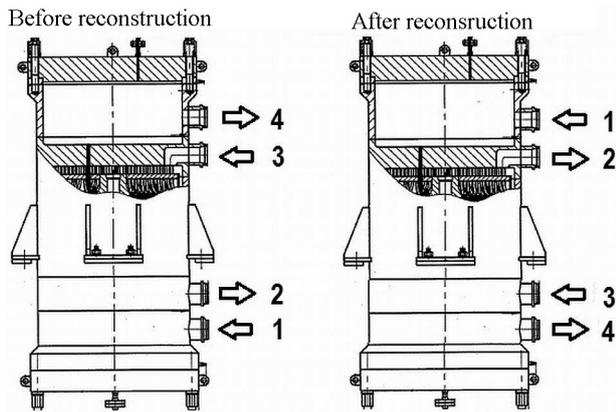


Figure 2. Connecting the SG blowdown RHE before and after reconstruction: 1 – hot water inlet from the SG; 4 – outlet of chilled water from the SG for treatment; 3 – cold water inlet after treatment; 2 – outlet of heated treated water back to the SG

Conclusions

The article presents the authors' view of possible further stages in developing operator support systems based on the OISS, the implementation of the functions of which is

currently being tested at NvNPP-II-1. The backbone components of the MOISS are the power unit software model and interactive procedures. The introduction of the OISS at the new generation power units, whether operating or under construction, will eliminate the information overload of operators and create conditions for a step-by-step increase in the automation level of the power unit control.

It is shown that the unit software model as part of the OISS can be used for

- analyzing the unit dynamic stability in the conditions of simulated modes associated with with equipment shutdown, ways of unloading the reactor plant with the subsequent updating of the thresholds of technological parameters, and time characteristics of processes;
- optimizing the thermal scheme of technological systems;
- modernizing the equipment piping schemes;
- improving the efficiency of heat exchange equipment by carrying out variants calculations and selecting its optimal design; and
- adjusting the existing FGC algorithms and developing new ones.

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