Application of Ecological Interface Design in NPP Operator Support System

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Abstract: Most publications confirm that ecological interface is a very effective tool supporting operators in recognition of complex unusual situations and in decision making. The present paper describes the experience of implementation of ecological interface concept for visualization of material balance in drum-separator of RBMK-type NPPs. Functional analysis of the domain area was carried out, which revealed main factors and contributors to the balance. The proposed ecological display was designed so that to facilitate execution of the most complicated cognitive operations, such as comparison, summarizing, prediction, etc. The experimental series carried out at NPPs demonstrated considerable reduction of operators' mental load, time of reaction and error rate.
Keyword: Ecological Interface Design, Work Domain Analysis, Model, Experimental Evaluation

1 Introduction

1.1 The concept of ecological interface

Ecological Interface Design (EID) is a framework for creating human-machine interfaces for complex systems[1]. 25 years experience of application of the EID concept in various domains (industrial, transportation, medicine, etc.) demonstrates that the ecological approach to visualization of information can improve situational awareness and support decision making process especially in unfamiliar and unanticipated complicated situations.

Some empirical experience has been obtained in application of EID for NPP process control tasks. In one of the first empirical studies[2] the BWR-type NPP operation was visualized as a combination of Rankine cycle and mass-energy balance diagrams. The authors reported that a typical comment of the test subjects was as follows: EID display would suit the novice operator training to build up his/her plant mental model. However, it is too crowded with information to easily understand the situation.

Very promised findings have been gathered from empirical studies conducted in frame of the OECD Halden Reactor Project[3]. N. Lau and G. A. Jamieson[4] demonstrated how the condenser subsystems of a boiling water reactor can be visualized using the EID principles. The laboratory studies conducted by them[5] have shown that ecological displays have a marked advantage in supporting operator performance during monitoring for unanticipated events as compared to mimic-based displays. At the same time, Burns e.a.[6] concluded that EID could be very effective in combination with traditional displays and with other innovative visualization approaches such as task-based displays. While EID demonstrates advantages in beyond-design basis scenarios where operators were unable to rely on procedures, it does not improve situational awareness in within-design basis scenarios[7]. However, six years later Carrasco e.a.[8] shown that EID interfaces support improved control task performance and greater control stability under normal operating conditions.

Similar display called as a High Performance Display (HPD) was proposed and experimentally tested by Rejas e.a.[9] They demonstrated that supervising with HPD adds an important value in terms of making early decisions to avoid more complex events. In all tested scenarios, the supervisors identified the malfunctions in the early stages and took the right decision to avoid any undesirable consequences.

There are two reasons why the EID can support operators in managing complex systems. First is that the EID provides systematical view on operation of complex system, which supports knowledge-based behaviour of operator. The EID is intended on visualization of a whole process instead of simple representation of individual process parameters and equipment status. Second feature of the EID is a special kind of graphics which transfers simple mental operations to the level of perception. Implementation of such graphical patterns provides "visualization" of mental calculations and reduces cognitive workload. R. Arnheim[10], who made an outstanding contribution to practical application of main gestalt psychology ideas, called this phenomenon as a "visual (perceptual) thinking". In according with his hypothesis, humans can make up a conclusion just on the base of perception of visual image shape instead of mental analytical processing of perceived information.

1.2 The domain area

This paper describes an experience acquired during application of the EID concept to support operators in management of a drum-separator (DS) at the RBMK-type (boiling water reactor) NPP. DS is an extremely important system providing steam for the turbine and water for cooling the reactor. Water flowing through the reactor boils and turns into a steam and water mixture. This mixture is released to four DSs where steam and water to be separated from each other. DS is a horizontal cylindrical vessel approximately 30 metres long and 2,3 metres in diameter. Working pressure and temperature in the DS are 6,57 MPa and 284 °C, respectively. These parameters make condition nearly the saturation line. The steam separated in the DS is transferred to the two turbines after which the steam is condensed. Then the condensate is deaerated and pumped by the feed water pumps into the bottom part of the DSs where the feed water mixes with the water separated from the steam.

DS looks like a busy crossroad where at least eight streams meet (Fig. 1). DS is very sensitive to any disturbance appearing at NPP. Operators must avoid approaching the setpoints which activate reduction of power or emergency shutdown. In normal conditions, the level is maintained by two automatic controllers. First controller works during low level of thermal power when steam and water flow rates are quite small. Second controller is used under normal operation and during anticipated disturbances. However, operators could face the challenge when dealing with start-up conditions, making transfer from the first controller to the second one, as well as when large disturbances occur. In such situations operator maintains level of water in the DSs manually. In order to compensate a disturbance, operator should govern one of three regulating valves and adjust feed water flow until the material balance between all incoming and outcoming flows is established. When reducing the flow, the operator must consider the permissible minimum of the flow rate which value depends on current reactor power. The task is complicated by the presence of nonlinearity, time lags (the reaction of water level in DS may be delayed by 40 seconds after control action has been done) and paradoxical behaviour of the water level (which looks as fall of water level when operator increases flow of the feed water).

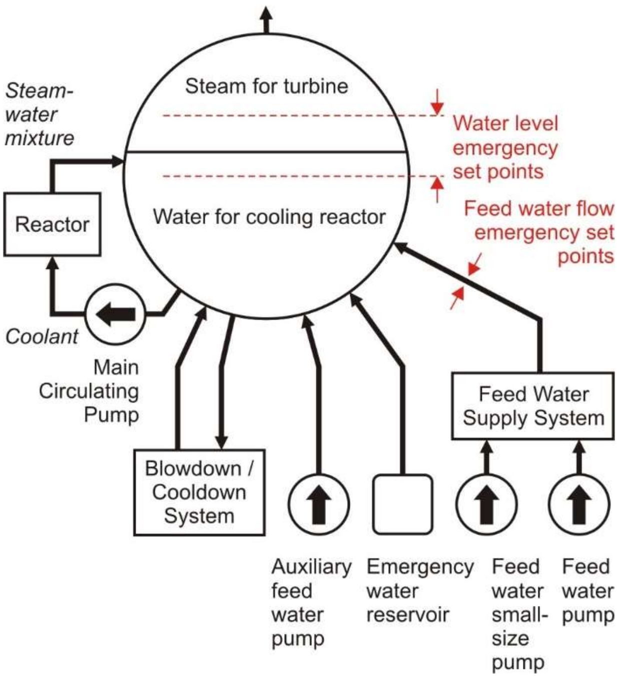

Fig. 1 Simplified diagram of the flows through the DS.

12 events at three NPPs caused by the fact that operators committed errors when trying to keep appropriate level in DS have been revealed in result of analysis of operational experience. The analysis demonstrated that operators often misunderstand situation and perform wrong control actions resulting in reactor shutdown. A few additional events occurred because the operators missed level of water in deaerator and condenser when trying to keep level in DS. When regulating flows in DS, operators must consider other secondary loop equipment as a holistic

system in term of mass conservation low. Thus, we revealed both reasons for implementation of the EID approach, namely heavy cognitive workload and systemic character of thinking.

2 Methodology

2.1 Work domain analysis

Usually, the functional analysis and the task analysis are used as the basic tools for ecological display designing. First approach called as the Work Domain Analysis (WDA) describes structure of complex system as a hierarchy of five levels representing functional purposes, abstract functions, generalized functions, physical functions and physical forms[11]. WDA does not refer to particular operational situations and therefore it does not take into account operator's tasks. However, the WDA can be supplemented by the Hierarchical Task Analysis (HTA) when ecological interface is being designed for supervisory control of carefully explored system[12].

As it was mentioned above, the task of DS manual control includes not only monitoring and analysis of DS parameters but also consideration of adjoining systems status. Functional analysis (or WDA) is an appropriate tool for identification of the work domain boundaries which should be involved into further consideration. In the present study a simplified modification of the WDA methodology[13] is used for functional decomposition of the work domain. The hierarchy of functions is shown in Fig. 2 and consists of three levels, namely

- *abstract functions* describing the plant operation in terms of physical processes, such as transition or conversion of energy;
- *process functions* describing the way by which abstract functions are performed (in fact, NPP operation is interaction of process functions);
- *process equipment* (e.g., pumps, heat exchangers, pipelines, etc.) providing realization of process functions.

2.2 Prognostic model

Functional analysis identified all the material flows, the equipment and the factors influencing status of DS. This information is used for development of structure of mathematical model describing dynamics of the main DS parameters, such as the level of water and the pressure of steam.

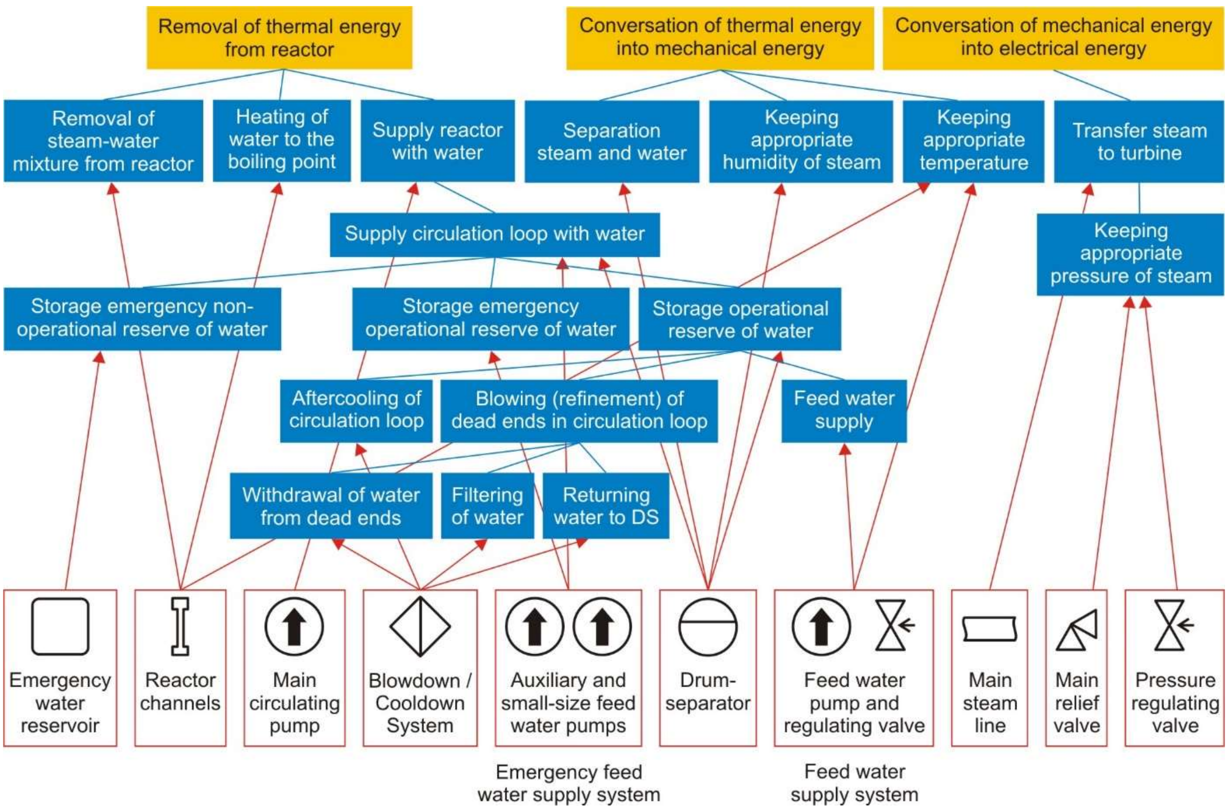

Fig. 2 Hierarchy of functions performed by drum-separators and adjoining systems.

The following assumptions are accepted in the differential equation system which describes DS as a tank with heat exchange using point approximation:

- steam and water temperatures are equal (i.e. the thermodynamic non-equilibrium of the phases in DS is not considered);
- the presence of uncondensed gas in steam and water is not considered;
- the pressures in the bottom and top parts of DS are equal.

The following differential equations based on the methodology for calculation of pressure vessels[14] constitute a dynamic model of DS:

- the equation of conservation of mass in DS

$$\frac{d}{d\tau}(M_{\mathrm{w}} + M_{\mathrm{s}}) = G_{\mathrm{m}} - G_{\mathrm{s}} - G_{\mathrm{w}} ;$$

- the equation of conservation of energy in DS

$$\frac{d}{d\tau}(M_{\mathrm{w}} h'(p) + M_{\mathrm{s}} h''(p) - Vp) =$$
$$= G_{\mathrm{m}} h_{\mathrm{m}} - G_{\mathrm{s}} h''(p) - G_{\mathrm{w}} h'(p) ;$$

- the equation of conservation of DS volume

$$\frac{d}{d\tau}(M_{\mathrm{w}} v'(p) + M_{\mathrm{s}} v''(p)) = 0 ,$$

where M_{w} – mass of water in DS; M_{s} – mass of steam in DS; G_{m} – mass flow of steam-water mixture from reactor to DS; G_{s} – mass flow of steam from DS to turbine; G_{w} – mass flow of water from DS to circulation loop; p – pressure in DS; τ – time; $h'(p)$ – specific enthalpy of water in DS; $h''(p)$ – specific enthalpy of steam in DS; V – DS volume; h_{m} – specific enthalpy of steam-water mixture at reactor output;

$$h_{\mathrm{m}} = h'(p_{\mathrm{r}})(1 - x) + h''(p_{\mathrm{r}})x$$

$h'(p_{\mathrm{r}})$ – specific enthalpy of water at reactor output (specific enthalpy of water in saturation state under pressure p_{r}); $h''(p_{\mathrm{r}})$ – specific enthalpy of steam at reactor output (specific enthalpy of dry saturated steam under pressure p_{r}); p_{r} – pressure at reactor output; x – mass steam content in steam-water mixture at reactor output; $v'(p)$ – specific volume of water in DS in saturation state under pressure p; $v''(p)$ – specific volume of steam in DS (specific volume of dry saturated steam under pressure p).

The SimPort© software was used for preliminary testing and validation of the model. SimWort© is a real-time shell system which have been intensively used for development of full scope simulators for heat and nuclear power plants[15].

3 Ecological display design

3.1 The image for support of perception

Functional and task analysis revealed a number of cognitive operations to be performed by operator toward to situational awareness and control decision making. Then all the cognitive operations were analysed in terms of required information, complexity, time pressure, human-machine interface and existing means to attract operator's attention. As it was mentioned, the previous operational experience demonstrates that operators often misunderstand situation and perform wrong control actions resulting in reactor shutdown.

The main purpose of new interface is suitable representation of information supporting operator in recognition of all contributors to material balance in DS as well as in understanding of interrelationships between these contributors and in awareness of how his actions may influence on the rest part of station.

The central part of the proposed ecological display (Fig. 3) contains the circle depicting the DS. Level of water is indicated by the scale located on the right of the circle. Water is shown by blue filling of the circle.

The level of water in DS can be controlled by adjustment whether of steam consumption or water supply. So, the main operation is a comparison between summary incoming (steam-water water mixture from the reactor, water from blowdown system, water from feed water supply system, and water from emergency reservoir) and outcoming (steam for turbine, water to the reactor, water to blowdown system) flows. All these flows are summarized into two horizontal bar charts allocated above and below the circle depicting the DS. The upper bar chart is immovable and indicates flow of steam from DS to turbine. The lower bar chart consists of four parts indicating feed water flow, emergency water flow, the difference between intake and return blowdown water, and the difference between intake and return of water to supply hydrostatic bearings of the main circulating pumps.

Bar chart is very simple and effective tool for visualization of addition and subtraction operations. Length of bar becomes longer when a positive value is summarized, or becomes shorter in case of negative value. The bar is directed to the left or to the down when the sum is negative.

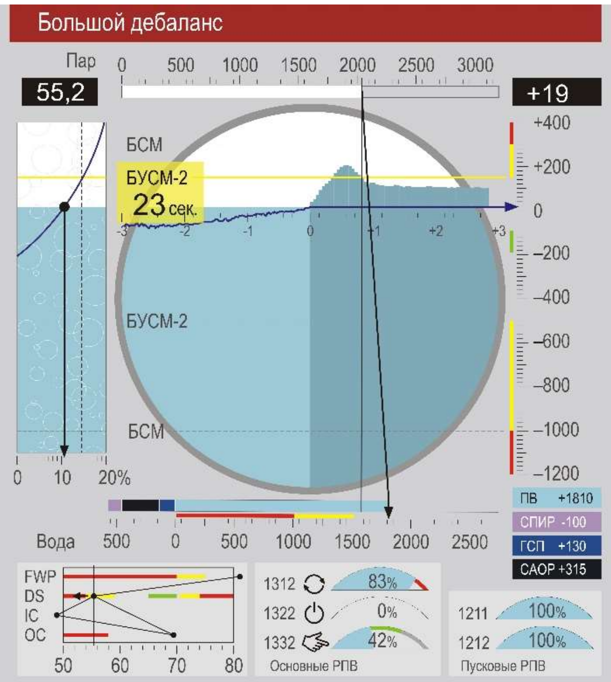

Fig. 3 The ecological display for monitoring of DS at the Smolensk NPP.

However, this algorithm is inapplicable in our situation because one of the bar chart components, namely feed water flow indicator must not be resized. Operator should permanently monitor this parameter in order to avoid activation of the reactor emergency protection induced by falling of the flow below setpoint. This means that the bar indicating the feed water flow together with the emergency setpoints should be indicated on its own account. In other words, the feed water bar must not become shorter even in the case when all the other flows have negative values. This circumstance requires searching of alternative approach for visualization of the subtraction operation. Movement of bar chart to the left is used as an alternative.

The balance between steam flow (upper bar chart) and summarized water flow (lower bar chart) is visualized by means of line connecting the ends of the bars. The line is oriented vertically when both the flows are equalized, and is inclined in case of imbalance. In this case operator should govern regulating valves and adjust water flow to the current steam flow (it should be noted that the steam flow is an independent parameter while the feed water flow is a dependent variable to be regulated manually or automatically). In order to support operator in identification of target water flow value a vertical line is dropped from the end of the upper bar.

The circle depicting DS is divided by color into two symmetrical parts. The left part contains a trend chart indicating historical information about behaviour of water level during previous three minutes, while the right part indicates prognosis for the next three minutes. Visualization of prognosis supports operator in estimation of the effect from his control actions. The importance of this prognosis can be illustrated by the following scenario (Fig. 4). Operator opens the regulating valves in order to increase the flow of feed water when the level in DS begins to fall (time point 1). The more the level falls the more water to be injected. However, the temperature of incoming feed water is considerably less than the temperature of the medium inside DS. This leads to decrease of steam concentration and to shrinkage of the steam-water mixture inside DS. In other words, an additional feed water may cause further falling of the level instead of the increasing as it is expected by operator. To avoid overrunning the lower setpoint, operator increases the feed water flow (time point 2) more. This does not go on for a long time. The water is heated after just one circulation through the reactor, and the level begins to increase extremely sharply (time point 3). Despite the fact that operator immediately reduces the feed water flow (time point 4), this result in exceeding the upper setpoint (time point 5).

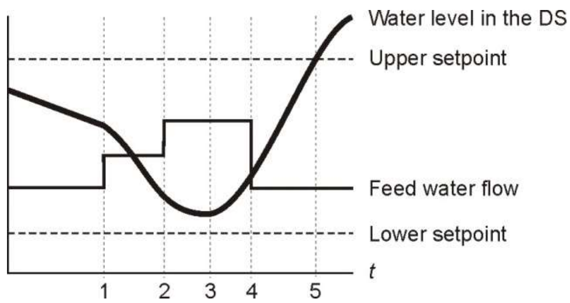

Fig. 4 Unexpected behaviour of water level in DS when operator is trying to avoid achievement of the lower setpoint[17].

A countdown display indicating the time available until the level will have overcame setpoint appears in case of prognosis reveals a threat of achievement this setpoint during next three minutes.

Next important information which should be gathered and monitored by operator is a relationship between pressures in various parts neighboring to DS. There are two conditions to be taken into account. First, some difference between any pair of pressures should be kept in order to ensure flow of medium in correct direction. Second, certain balance between pressure and temperature should be maintained in order to keep process below the saturation line and to avoid cavitation of pumps.

To support operator in situation awareness all the required pressure parameters are combined into the pressure diagram where the dynamically calculated setpoints are also displayed. Under normal conditions all setpoints are indicated as grey bars which are colored to yellow or red when parameter is approaching to abnormal region. Similar representation is used for visualization of the water level in DS and the feed water flow setpoints.

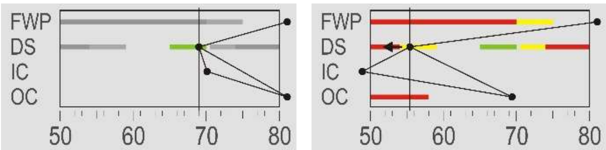

Fig. 5 Normal (left) and abnormal (right) pressure profiles.

3.2 Technological aspects of EID development

Ecological displays designed in the present study as well as the displays described in the most of cited publications contain untypical graphical objects with complicated behaviour (see an example in Fig. 6). Such objects usually are not supported by standard SCADA system tools. This fact is the main reason why original software should be developed. Of course, use of non-standard tools leads to unproductive efforts and complicates the processes of development and validation.

In contrast to conventional mimic diagrams (flow charts) the ecological interface requires detailed development of graphics. It is especially important to ensure proper behaviour of graphical objects in response to change of process parameters through the whole range of their values. An auxiliary tool was developed in order to provide designer with soft control panel which allow to change smoothly any parameter independently from other ones (Fig. 7).

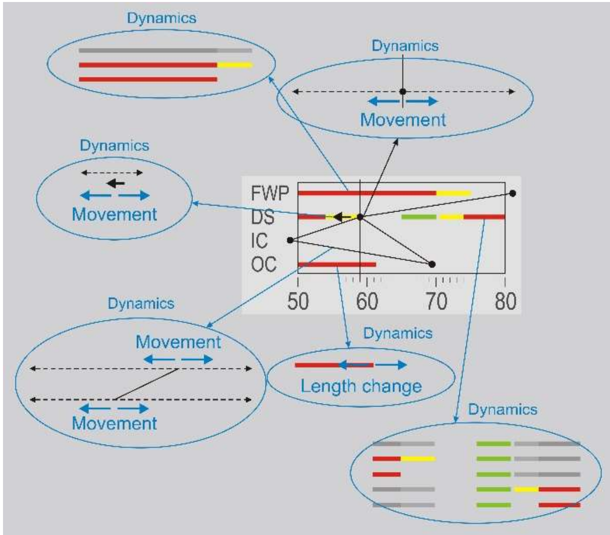

Fig. 6 An example of description of untypical graphical objects.

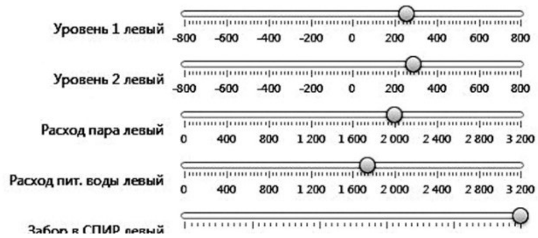

Fig. 7 Fragment of soft control panel for fine-tuning of EID.

Besides the tool for tuning of the EID and the module for visualization, the final software package includes the module for interaction with NPP I&C system, the module for recording of log (archive), and the “player” for off-line running the scenarios previously recorded in the log[16].

4 Empirical evaluation of the EID

Two experimental series were carried out at the Full Scope Simulators (FSS) of Leningrad (LNPP) and Smolensk (SNPP) NPPs. Both stations are 1000 MW RBMK-type NPP. FSS at both stations are an accurate replica of real main control room. At LNPP the EID was displayed at the additional external VDU installed on conventional desk while at SNPP it was displayed at the VDU which is a part of the station I&C system and is installed at vertical conventional panel (Fig. 8).

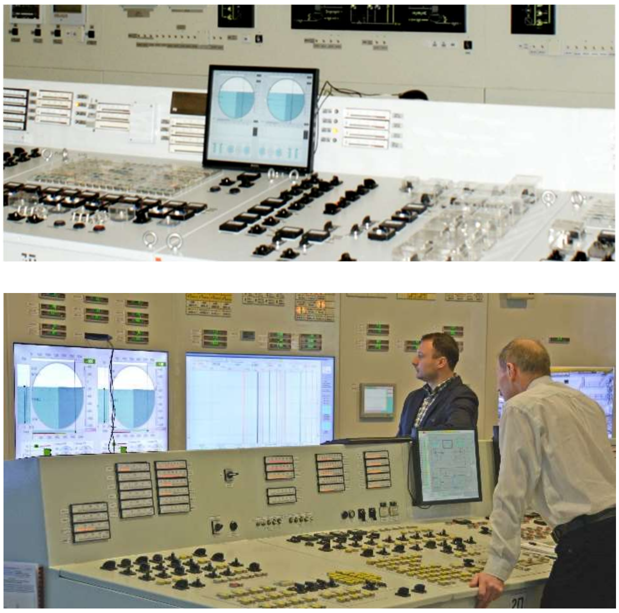

Fig. 8 Testing of the ecological display at LNPP (upper photo) and SNPP (lower photo)

The experimental programme includes familiarization of participants with the EID followed by interview or filling of the check list, execution of the specially designed exercises, running the realistic scenarios and filling the questionnaire[17].

The following six hypotheses were examined during the experimental series:

1) the ecological display and its components are intuitively obvious to operators without any additional explanations;
2) all graphic objects and their layout are easy perceivable and don't break established professional user stereotypes;
3) the operators are able to recognize imbalance and trend of water level sooner than using conventional interface;
4) the ecological display reduces mental load and provides more efficient feedback from control actions in comparison with conventional interface;
5) the ecological display quickens identification of source of imbalance and facilitates decision making as compared with conventional interface;
6) the ecological interface reduces probability of errors committed by operators during control of water level.

All these hypotheses were confirmed. The ecological display was slightly improved in result of analysis of feedback provided by the operators regarding obviousness and conformity of the display (hypotheses 1, 2). Statistical analysis of response time and interviewing of the operators revealed that in 80% of all cases the ecological display quickens execution of task two, three and more times. 20% of the tasks were performed more quickly with the use of conventional interface (hypothesis 3). Analysis of accuracy and smoothness of the control actions / regulation processes and interviewing of the operators proved hypothesis 4. Filling the questionnaire, all the participants indicated that the ecological display provides much more holistic representation of the information about the material flows through the DS, which confirms hypothesis 5. Analysis of human errors resulting activation of emergency protection showed that the relative frequency of the errors committed during the work with the ecological display is 0,05. Number of errors essentially increased (the relative frequency is 0,19) when the operators were using conventional interface, which confirms hypothesis 6.

5 Conclusive remarks

The many years' practical experience gathered from designing and experimental evaluation of the ecological interface allows us to draw certain conclusions. First of all, the "ecological interface" as a term is ambiguous. This term is easily recognized by those researchers who are aware of the ecological approach to visual perception by J. Gibson[18] or studies in the area of ecological psychology. Non-specialists perceive this term more cautiously. In order to make things clear many researchers use other terms, such as advanced display, high performance display, etc.

NPP operators don't have a consensus with respect to the ecological interface. Most of them speak of ecological approach with great skepticism. They think that the ecological interface is not capable to replace conventional mimic based VDU formats. On the other hand, use of ecological display as an operator support system together with conventional mimic interface forces operators to constantly switch their attention and can lead to superimposition of two different stereotypes of perception and, as a result, can lead to errors.

Our experiments and discussions with the operators demonstrated that the most experienced operators show the most skepticism about the ecological interface. Nevertheless, the impartial (numerical) analysis of their work revealed that they manage complex situations more efficiently with the ecological display in comparison with the conventional interface. Unfortunately, we did not use the well-known methods for evaluation of cognitive load in this study relying upon the reports and self-assessment which have been made by the operators right after execution of the exercises.

In whole, the evaluation programme carried out at the Leningrad and Smolensk NPP full-scope training simulators has shown a prominent advantage of the ecological display as compared with traditional interface.

As well as in many other studies, it was revealed that the efficiency of the ecological interface depends on situation. Some functional capabilities of the ecological display were extremely helpful in particular situations, while in other situations the efficiency of these functions was not so prominent. However, the main finding is that ecological interface essentially reduces error rate although it not always facilitates quickness of operator's reaction.

It is evident that the existing trend towards increasing the level of automation of NPP control can essentially change the role of operator. The future operator will perform more functions as an observer and analyst, rather than just a performer of operational procedures. Similar situation takes place in passenger aviation where automatic control systems can fully replace pilots in the most of operations. It will inevitably lead to replacement of the existing interface to those which provides an efficient support of cognitive processes and analysis of situation. However, such interface cannot be developed as a simple graphical video format. They should be accompanied by more sophisticated logical processing of equipment state, operational conditions and control actions. Such processing moves ecological display to the category of intellectual systems.

One more important function which should be done by ecological display in the future is a possibility to perform control actions via such display. Ecological approach to visualization simplifies setting target value when managing process parameters. For example, it may be a drag transfer of line or point to some target value. Such methods are used for many years by the designers developing user interface for commercial gadgets, such as tablets, smartphones, etc. Moreover, currently a new generation of users has grown who consider such control gestures as a natural and usual aspect of their life.

Acknowledgement

The authors express acknowledgements to full scope simulator instructors Leonid Tarasov, Andrey Podkopaev (LNPP) and Sergey Torgov (SNPP), who spent many hours in discussion of the technological process details, explained everything with inexhaustible patience and made inestimable contribution to implementation of the evaluation programme. Also, we are grateful to Mikhail Lipov for his outstanding contribution to realization, validation and evolutionary improvement of the simulation model.

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