Nuclear Engineering and Technology 50 (2018) 619–626

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Application of ecological interface design in nuclear power plant (NPP) operator support system

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A R T I C L E I N F O

Article history:
Received 31 January 2018
Received in revised form
9 March 2018
Accepted 11 March 2018
Available online 23 March 2018

Keywords:
Ecological Interface Design
Experimental Evaluation
Model
Work Domain Analysis

A B S T R A C T

Most publications confirm that an ecological interface is a very efficient tool to supporting operators in recognition of complex and unusual situations and in decision-making. The present article describes the experience of implementation of an ecological interface concept for visualization of material balance in a drum separator of RBMK-type NPPs. Functional analysis of the domain area was carried out and revealed main factors and contributors to the balance. The proposed ecological display was designed 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.

1. Introduction

1.1. Concept of ecological interface

Ecological interface design (EID) is a framework for creating human–machine interfaces for complex systems [1]. Twenty-five years of 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 the 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], boiling water reactor (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 participants was as follows: EID display would suit the novice operator in training to build his/her plant mental model. However, it is too crowded with information to easily understand the situation.

Very promising findings have been gathered from empirical studies conducted in frame of the The Organisation for Economic Co-operation and Development (OECD) Halden Reactor Project [3]. Lau and Jamieson [4] demonstrated how the condenser subsystems of a boiling water reactor can be visualized using EID principles. Their laboratory studies [5] have shown that ecological displays have significant advantages in supporting operator performance during unanticipated event monitoring as compared to mimic-based displays. At the same time, Burns et al. [6] concluded that EID can be very efficient in combination with traditional displays and with other innovative visualization approaches such as task-based displays. They found that while EID demonstrates advantages in beyond-design basis scenarios in which operators are unable to rely on procedures, it does not improve situational awareness in within-design basis scenarios [7]. However, 6 years later, Carrasco et al. [8] demonstrated that EID interfaces ensure better control task performance and greater control stability under normal operating conditions.

A similar display, called a "high performance display" (HPD), was proposed and experimentally tested by Rejas et al. [9]. They demonstrated that supervision with HPD adds an important value in terms of making early decisions to avoid more complex events. In all tested scenarios, the supervisors identified malfunctions in the early stages and took the right decisions to avoid any undesirable consequences.

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https://doi.org/10.1016/j.net.2018.03.005

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

1.2. Domain area

This article describes the experience gained during application of the EID concept to support operators in management of a drum separator (DS) at an RBMK-type (boiling water reactor) NPP. DS is an extremely important system providing steam for the turbine and water for reactor cooling. 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 are separated. DS is a horizontal cylindrical vessel approximately 30 m long and 2.3 m in diameter. Working pressure and temperature in the DS are 6.57 MPa and 284°C, respectively. With such parameters, the conditions are close to those of a saturation line. Steam separated in the DS is transferred to two turbines, and afterward the steam is condensed. Then, the condensate is deaerated and pumped by feed water pumps into the bottom part of the DSs, where the feed water mixes with the water separated from the steam.

The DS looks like a busy crossroads where at least eight streams meet (Fig. 1). It is very sensitive to any disturbance appearing at the NPP. Operators must avoid approaching the setpoints that activate reduction of power or emergency shutdown. In normal conditions, the level is maintained by two automatic controllers. The first controller works during low level of thermal power when steam and water flow rates are quite small. The second controller is used under normal operation and during anticipated disturbances. However, operators may face certain challenges when dealing with start-up conditions, switching from the first controller to the second one, as well as when major disturbances occur. In such situations, operator maintains the level of water in the DSs manually. To compensate for any disturbance, the operator must adjust one of the three regulating valves and adjust the feed water flow until a material balance between all incoming and outgoing flows is established. When reducing the flow, the operator must keep in mind the permissible minimum flow rate, which depends on the current reactor power. The task is made more complicated by the presence of nonlinearity, time lags (the reaction of the water level in the DS may be delayed by 40 seconds after control action has been taken), and paradoxical behavior of the water level (there can seem to be a fall of the water level when the operator increases the feed water flow).

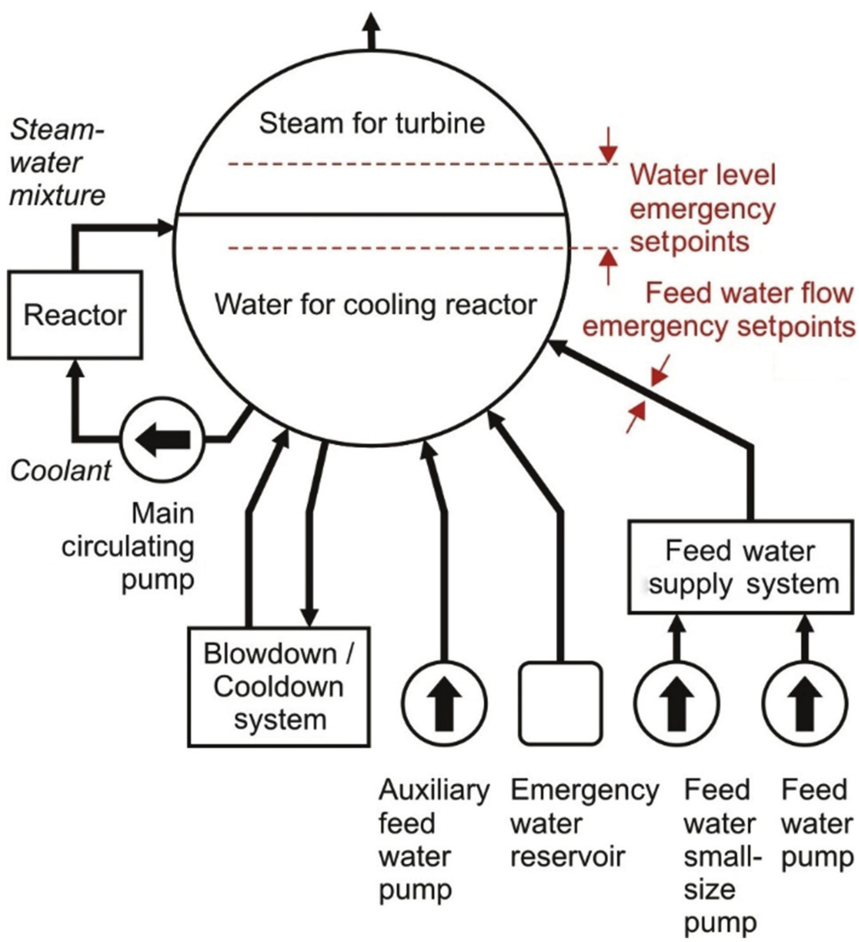

Fig. 1. Simplified diagram of the flows through the DS.
DS, drum separator.

Following the operational experience analysis, 12 events were identified at three NPPs when operators had made errors trying to maintain an appropriate level in the DS. The analysis demonstrated that operators had often misunderstood the situation and performed wrong control actions, resulting in reactor shutdown. A few additional events had occurred because operators had overlooked the water level in the deaerator and the condenser when trying to maintain the level in the DS. When regulating flows in the DS, operators must consider other secondary loop equipment as a holistic system in terms of the mass conservation law. Thus, we revealed two reasons for implementation of the EID approach, namely heavy cognitive workload and systematic character of thinking.

2. Methods

2.1. Work domain analysis

Usually, functional analysis and task analysis are basic tools for ecological display design. The first approach, called "work domain analysis" (WDA), describes the structure of a 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 tasks. However, WDA can be supplemented by hierarchical task analysis in cases in which an ecological interface is being designed for supervisory control of a well-known system [12].

As mentioned above, the task of DS manual control includes not only monitoring and analysis of DS parameters but also consideration of the status of adjacent systems. Functional analysis (or WDA) is an appropriate tool for identification of the work domain boundaries that should be involved in further consideration. In the present study, a simplified modification of 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 ways in which abstract functions are performed (in fact, NPP operation is the interaction of process functions); and
– *process equipment* (e.g., pumps, heat exchangers, pipelines, etc.) implementing the process functions.

2.2. Prognostic model

Functional analysis was used to identify all material flows, equipment, and factors influencing the status of DS. This information was used to develop the structure of a mathematical model describing the dynamics of the main DS parameters, such as water level and steam pressure.

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

– steam and water temperatures are equal (i.e., the thermodynamic nonequilibrium of the phases in DS is not considered);

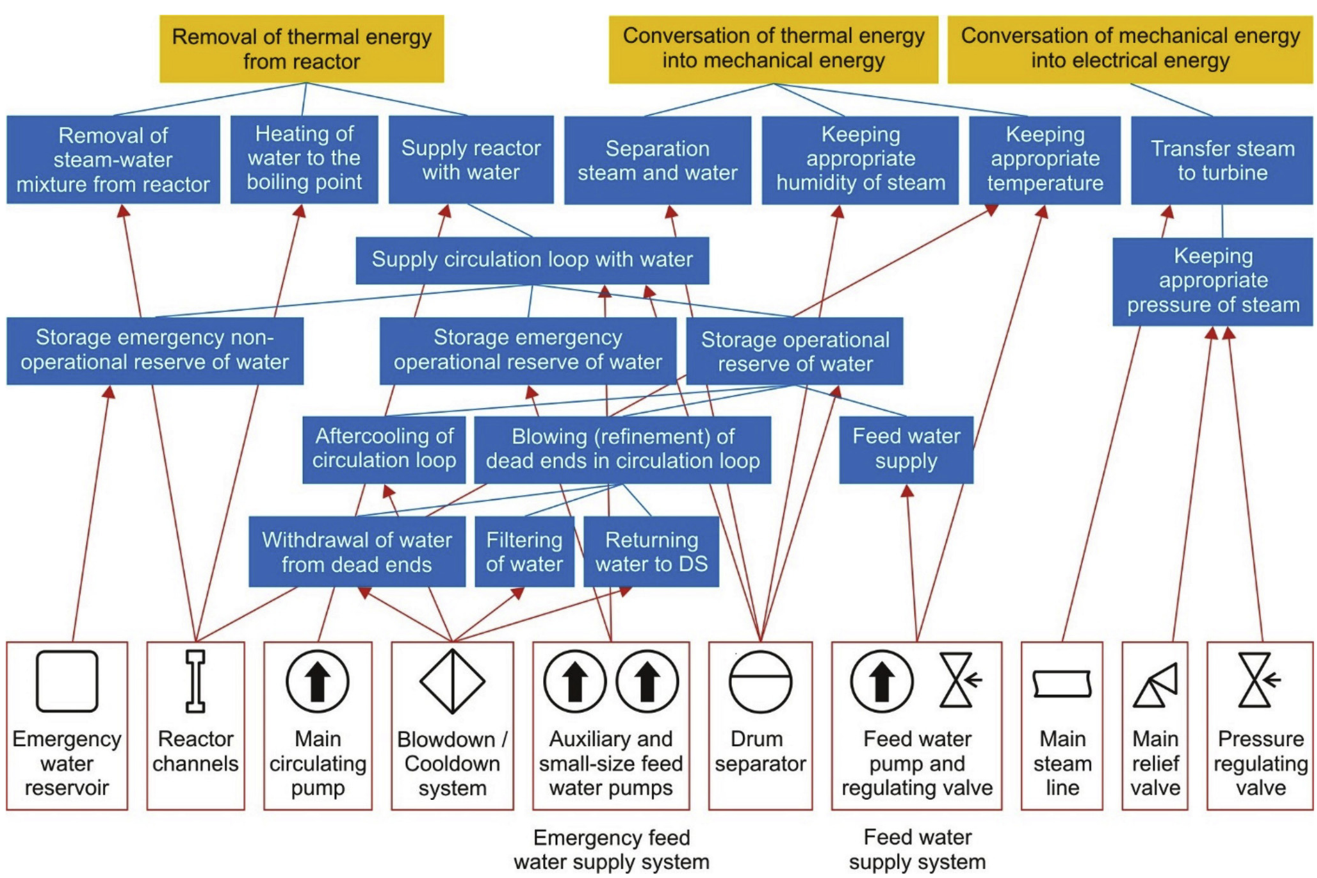

Fig. 2. Hierarchy of functions performed by drum separators and adjoining systems.
DS, drum separator.

– the presence of uncondensed gas in steam and water is not considered; and
– 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

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

– the equation of conservation of DS volume

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

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; and 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});

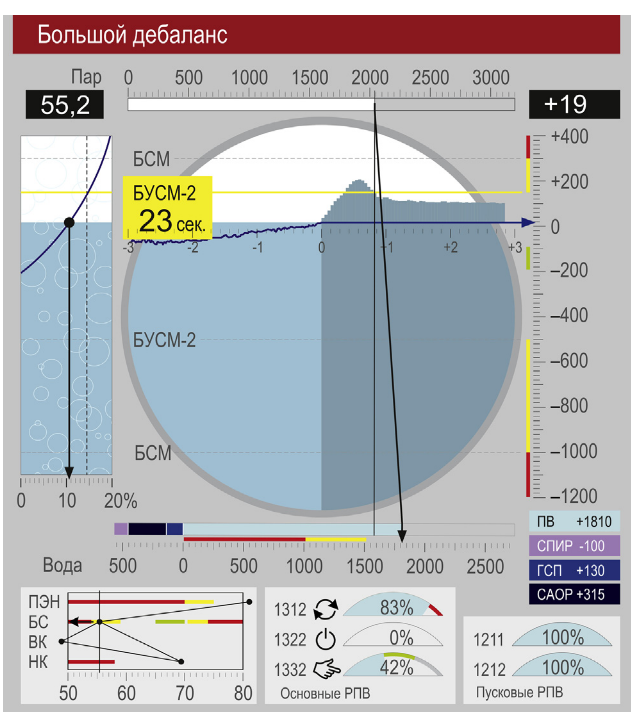

Fig. 3. The ecological display for monitoring of DS at the Smolensk NPP.
DS, drum separator; FWP, Feed Water Pump; PH, pressure header; SH, suction header.

$h''(p_{\mathrm{r}})$ = 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; and $v''(p)$ = specific volume of steam in DS (specific volume of dry saturated steam under pressure p).

SimPort© software was used for preliminary testing and validation of the model. SimPort© is a real-time shell system that has been used extensively for development of full scope simulators for thermal and nuclear power plants [15].

3. Ecological display design

3.1. Images for support of perception

Functional and task analysis revealed a number of cognitive operations to be performed by an operator to require situational awareness and the ability to make control decisions. Then, all cognitive operations were analyzed in terms of the required information, complexity, time pressure, human–machine interface, and existing means to attract operator's attention. As mentioned, previous operational experience demonstrates that operators often misunderstand situations and perform wrong control actions, resulting in reactor shutdown.

The main purpose of the new interface is to provide proper representation of information so that an operator can identify all contributors to the material balance in the DS, understand the interrelations between these contributors, and know how his/her actions may influence the rest of the plant.

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

The level of water in the DS can be controlled by adjusting either the steam consumption or the water supply. So, the main operation is the comparison of all incoming (steam–water mixture from the reactor, water from the blowdown system, water from the feed water supply system, and water from the emergency reservoir) and outgoing (steam for the turbine, water to the reactor, and water to the blowdown system) flows. All these flows are summarized into two horizontal bar charts located above and below the circle depicting the DS. The upper bar chart is stationary; it indicates the flow of steam from the DS to the turbine. The lower bar chart consists of four parts that show the feed water flow, the emergency water flow, the difference between the intake and the return blowdown water, and the difference between the intake and the return of water for hydrostatic bearings of the main circulating pumps.

A bar chart is a very simple and efficient tool for visualization of addition and subtraction operations. The bar becomes longer when a positive value is added or becomes shorter in the case of a negative value. The bar is directed left or down when the sum is negative.

However, simple change of the bar length is inapplicable in our case because one of the bar chart components, namely the feed water flow indicator, shall remain unchanged. The operator must monitor this parameter continuously to avoid activation of the reactor emergency protection due to flow below the setpoint. This means that the bar indicating the feed water flow, together with the emergency setpoints, must be shown separately. In other words, the feed water bar cannot get shorter even when all other flows are negative. This circumstance requires an alternative approach for visualization of the subtraction operation. As an alternative, the bar chart has been moved to the left.

The balance between steam flow (the upper bar chart) and total water flow (the lower bar chart) is visualized by means of a line connecting the ends of the bars. The line is oriented vertically when both the flows are equalized and is inclined in cases of imbalance. In this case, the operator must govern the regulating valves and adjust the 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). To support the operator in identification of the target water flow value, a vertical line goes down 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 the history of water level behavior for the previous 3 minutes, while the right part indicates a prognosis for the next 3 minutes. Visualization of the prognosis supports the operator in estimation of the effects of his/her control actions. The importance of this prognosis can be illustrated by the following scenario (Fig. 4). The operator opens the regulating valves to increase the flow of feed water when the level in the DS begins to fall (time point 1). The more the level falls, the more water has to be injected. However, the temperature of the incoming feed water is considerably lower than the temperature of the medium inside the DS. This leads to a decrease of steam concentration and shrinkage of the steam–water mixture inside the DS. In other words, additional feed water may cause a further fall of the level instead of the rise expected by the operator. To avoid overrunning the lower setpoint, operator increases the feed water flow (time point 2) even more. This does not go on for a long time. Water is heated after just one circulation through the reactor, and the level begins to increase rapidly (time point 3). Despite the fact that operator immediately reduces the feed water flow (time point 4), this results in exceeding the upper setpoint (time point 5).

If the prognosis reveals a threat of reaching this setpoint in the following 3 minutes, a countdown display appears that shows the time available until the level exceeds the setpoint.

Another important piece of information that should be acquired and monitored by the operator is the relationship between the pressures in various parts close to the DS. There are two conditions to be taken into account. First, a certain difference between any pair of pressures must be kept to ensure that the medium flows in the correct direction. Second, a certain balance between pressure and temperature must be maintained to keep the process below the saturation line and avoid cavitation of the pumps.

To support operator situational awareness, all required pressure parameters are combined into a pressure diagram in which dynamically calculated setpoints are also displayed (Fig. 5). Under normal conditions, all setpoints are indicated as gray bars that become yellow or red when the parameter approaches the

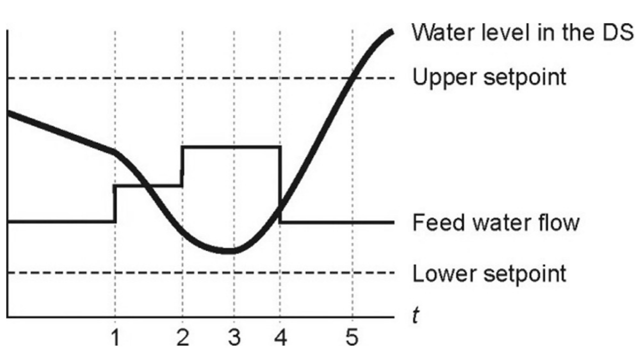

Fig. 4. Unexpected behavior of water level in DS when operator is trying to avoid achievement of the lower setpoint.
DS, drum separator.

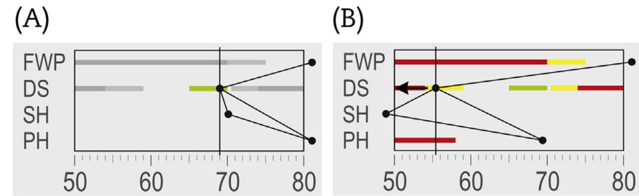

Fig. 5. Pressure profiles. (A) Normal. (B) Abnormal.
DS, drum separator; FWP, Feed Water Pump; PH, pressure header; SH, suction header.

abnormal range. A similar representation is used for visualization of the water level in the DS and the feed water flow setpoints.

3.2. Technological aspects of EID development

The ecological displays designed in the present study, as well as the displays described in the majority of the cited publications, contain nonstandard graphical objects with complicated behavior (see an example in Fig. 6). Such objects are usually not supported by standard supervisory control and data acquisition (SCADA) system tools. This fact is the main reason why original software has to be developed. Of course, the use of nonstandard tools leads to unproductive efforts and complicates the processes of development and validation.

Unlike conventional mimic diagrams (flow charts), the ecological interface requires detailed development of graphics. It is especially important to ensure proper behavior of graphical objects in response to changes of process parameters for the whole range of their values. An auxiliary tool was developed to provide designers with a soft control panel that allows them to change any parameter smoothly and independently from other ones (Fig. 7).

Apart from the tool for EID tuning and the module for visualization, the final software package includes a module for interaction with the NPP I&C system, a logging (archiving) module, and a "player" that runs off-line the scenarios previously recorded in the log [16].

4. Results

Two experimental series were carried out with the full scope simulators of the Leningrad NPP and Smolensk NPP. Both plants are 1,000 MW RBMK-type. Full scope simulators at both plants are full replicas of the real main control room. At Leningrad NPP, EID was displayed on an additional external video display unit (VDU) installed on a conventional desk, while at Smolensk NPP, it was displayed on a VDU that was part of the plant I&C system and was installed on a conventional vertical panel (Fig. 8).

The experimental program included familiarization of the participants with the EID, followed by an interview or filling out of a check list, execution of the specially designed exercises, running of the realistic scenarios, and filling out of a 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 graphical objects and their layouts are easily perceivable and do not break the established professional user stereotypes;
3) operators are able to recognize imbalances and trends of water level sooner than when using conventional interface;
4) the ecological display reduces mental load and provides more efficient feedback from control actions compared to the conventional interface;

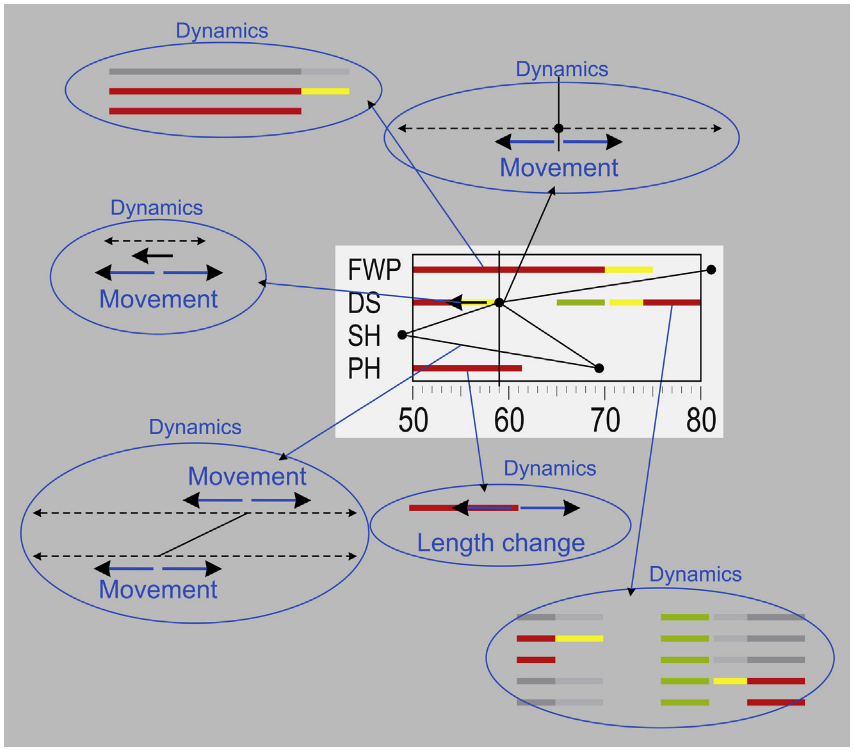

Fig. 6. An example of description of untypical graphical objects.
DS, drum separator; FWP, Feed Water Pump; PH, pressure header; SH, suction header.

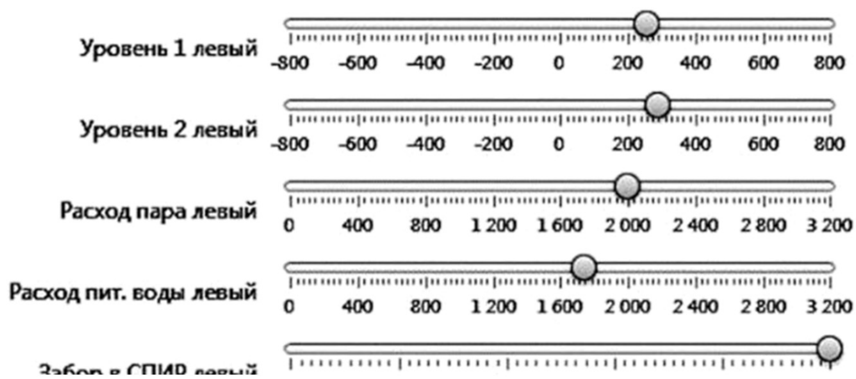

Fig. 7. Fragment of soft control panel for fine-tuning of EID.
EID, Ecological interface design.

5) the ecological display quickens identification of sources of imbalance and facilitates decision-making as compared to the conventional interface;
6) the ecological interface reduces the probability of human error in water level control.

All these hypotheses were confirmed. The ecological display was slightly improved following the analysis of the feedback provided by the operators in terms of clarity and consistency of the display (hypotheses 1, 2). Statistical analysis of response time and interviews with the operators revealed that in 80% of all cases the ecological display helped execute tasks two, three, and more times faster. Twenty percent of the tasks were performed faster with the use of the conventional interface (hypothesis 3). Analysis of accuracy and smoothness of the control actions/regulation processes and interviews with the operators proved hypothesis 4. In the questionnaires, all participants indicated that the ecological display provided much more holistic representation of information about the material flows through the DS, which confirms hypothesis 5. Analysis of human errors resulting in activation of emergency protection showed that the relative frequency of errors made when working with the ecological display was 0.05. The number of errors was much higher (the relative frequency is 0.19) when the operators were using the conventional interface, which confirms hypothesis 6.

5. Discussion

The many years' practical experience gained in design and experimental evaluation of ecological interfaces allow us to draw certain conclusions. First of all, "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 of Gibson

Fig. 8. Testing of the ecological display at LNPP (upper photo) and SNPP (lower photo). LNPP, Leningrad NPP; SNPP, Smolensk NPP.

[18] or studies in the area of ecological psychology. Nonspecialists perceive this term more cautiously. To make things clear, many researchers use other terms, such as advanced display, HPD, etc.

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

Our experiments and discussions with operators demonstrated that the most experienced operators show the most skepticism about the ecological interface. Nevertheless, impartial (numerical) analysis of their work revealed that they manage complex situations more efficiently with the ecological display as compared to the conventional interface. Unfortunately, we did not use any proven methods for evaluation of cognitive load in this study and relied on the reports and self-assessment made by the operators right after execution of the exercises.

On the whole, the evaluation program carried out at the Leningrad and Smolensk NPPs full-scope training simulators has shown a prominent advantage of the ecological display as compared to the conventional interface.

As has been the case in many other studies, it was revealed that the efficiency of the ecological interface depends on the 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 the ecological interface reduces the error rate considerably, although sometimes it does not ensure faster operator response.

It is evident that the existing trend toward increasing the level of automation in NPP control can essentially change the role of the operator. The future operator will perform more functions as an observer and analyst, rather than just a performer of operational procedures. The same is true for passenger aviation, where automatic control systems can fully replace pilots in most operations. This will inevitably lead to replacement of the existing interface with one that provides an efficient support of cognitive processes and analysis of situations. However, such an interface cannot be developed as a simple graphical video format. It 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 intelligent systems.

One more important function that should be added to the ecological display in the future is the possibility of performing control actions via the display. The ecological approach to visualization simplifies target value setting when managing process parameters. For example, it may allow a drag transfer of a line or point to some target value. Such methods have been used for many years by designers who develop user interfaces for commercial gadgets, such as tablets, smartphones, etc. Moreover, currently, a new generation of users have grown up who consider such control gestures natural and usual aspects of their lives.

Conflict of interest

There is no any conflict of interest. All the organizations provided official permission for publication of the article.

Acknowledgments

The authors express their acknowledgments 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 program. Also, they are grateful to Mikhail Lipov for his outstanding contribution to implementation, validation, and evolutionary improvement of the simulation model.

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