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Original Article

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

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ABSTRACT

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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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).

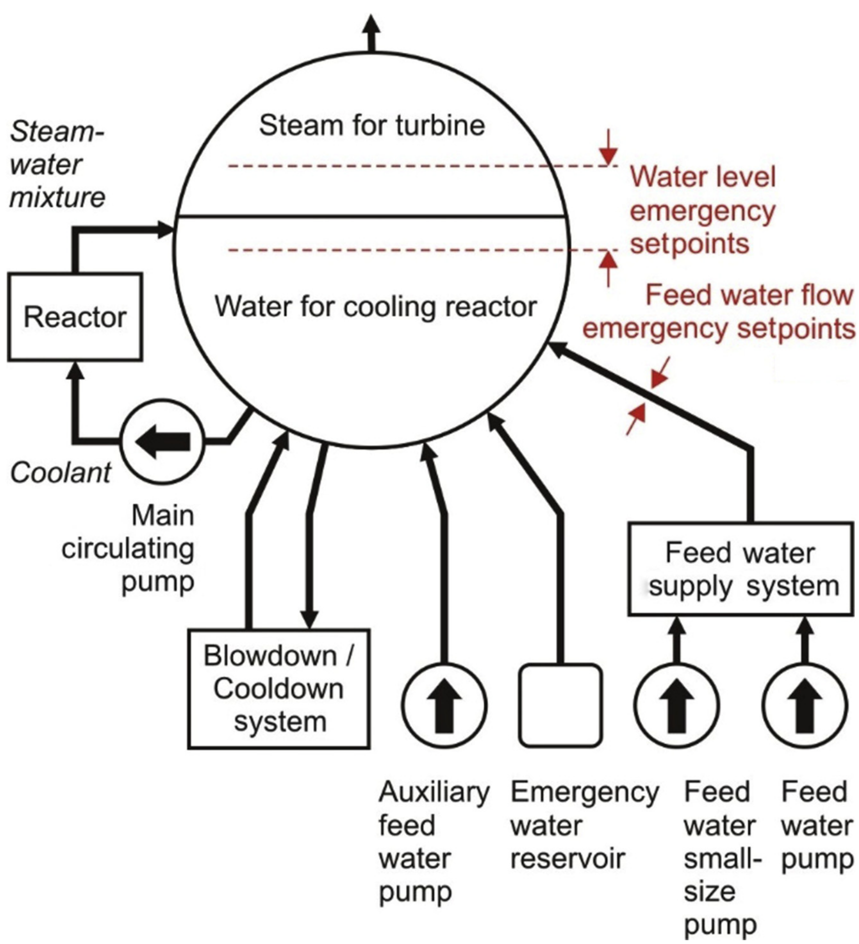

Fig. 1. Simplified diagram of the flows through the DS.
DS, drum separator.