Computer-Based Human-Machine Interfaces for Emergency Operation

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Abstract

The emergency operating procedures (EOPs) are fundamental for coping with emergency and accident situations in nuclear power plants. Researchers at the Halden Reactor Project have developed a design concept including computer-based EOPs and other displays to support the operators during emergency situations. The computer-based procedure system includes three displays: a symptom check display intended for monitoring EOP entrance criteria; a procedure selection and overview display; and a procedure performance display. A large screen display provides shared information viewable for all operators in the control room. This paper describes the design, implementation and initial testing of the displays in the HAlden Man Machine LABoratory (HAMMLAB). The original paper presented at the 10th International Topical Meeting on Nuclear Plant Instrumentation, Control and Human Machine Interface Technologies (NPIC&HMIT 2017) has been revised to include empirical results from a full-scope simulator study.

Keywords: computer-based procedures, large screen display, emergency operation

I. INTRODUCTION

The emergency operating procedures (EOPs) are seen as an important component of the defense in depth concept of nuclear operation [1]. The principle of defense in depth is based on the idea that there should be several layers of protection preventing unsafe conditions and release of radioactive material to the environment. The EOPs are intended to maintain safety functions and prevent core damage, or initiate mitigating actions by guiding the operators' course of actions in demanding situations. Most nuclear power plants currently in operation use paper-based EOPs. However, studies concerning the usage of paper-based EOPs have shown that prescribing activities and acting in accordance with procedures across different situations is not simple [e.g., 2, 3, 4]. In order to cover a range of conditions, the procedures are extensive and include a lot of material that may not be relevant for the task at hand. This complicates the navigation within and between procedures for the operators, who may unintentionally miss important information, skip steps or perform them in wrong order. Furthermore, the administrative processes to ensure procedure adherence such as place-keeping techniques and correct component verification may draw attention away from the primary task of safely controlling the plant.

In modernization of existing power plants and design of new builds, computer-based procedures present an opportunity to improve operator performance and overcome weaknesses associated with paper procedures as exemplified above. Better maintenance and tracking possibilities are also an important motivation for implementing computer-based procedures [5]. Computer-based procedure systems range from electronic replicas of the paper procedures to systems providing automatic supervision and execution of pre-defined actions [6]. The latter types of computer-based procedures will markedly affect the use of the EOPs. The main advantage of computer-based EOPs is the automatic gathering of dynamic information relevant to a procedure step, such as plant components, parameters and operational limits. This reduces the navigational tasks for the operators and supports monitoring of continuous steps and operational conditions. Computer-based procedures can also provide navigational links to other procedures and documents, and allow team members to monitor the procedure work progress from a different location. Possible disadvantages with computer-based procedure systems include failures of automatic process supervision and place-keeping functions [7], poorer readability in digital displays compared to paper, restrictions in the amount of information displayed and more cumbersome annotation functionality compared to using pen and paper. Finally, the operators may be forced to transfer to paper procedures in case of total loss of the computer-based procedure system [7].

This paper describes the design and initial testing of a computer-based procedure system and other displays to support the operators when entering symptom-based EOPs. These constituted parts of a computer-based HMI concept [8] that was implemented and tested on a boiling water reactor (BWR) simulator in the HAlden Man Machine LABoratory (HAMMLAB). The content of the emergency operating procedures was based on the original paper procedures available at a similar ABB plant (BWR 75). At the simulated plant the shift supervisor reads the procedure and the reactor operator normally performs the actions in the control room panels and desks. With our computer-based EOPs, performing actions and checks are expected to be easily manageable for the shift supervisor, while the reactor and turbine operators can perform detailed procedures included in the EOPs, check other important procedures and/or follow the status of the plant.

Similar to other computer-based procedure systems [e.g., 9, 10] the entry conditions for applying EOPs are automatically monitored. When one or more entrance criteria are met the procedure system highlights the relevant EOPs, but the operator decides what procedure to open. The procedure system also provides the process information needed to perform the procedure steps and highlights the parameters and components to be checked or maneuvered, but does not execute actions. The reason is that all safety systems start automatically after actuation of the RPS, and that the plant design requires no manual actions during the first 30 minutes. Mitigation systems require no manual actions during the first eight hours. If the automation fails, the operators should manually try to start the systems by following procedures included in the EOPs. Automatic execution would only be possible for a few steps, as most steps in these procedures are local actions. The control room operator executes all actions manually from a single screen presenting the relevant process displays. The integration of the EOPs and the process displays seems to be a unique characteristic of the system compared to existing computer-based procedure systems [e.g., 7, 9, 10, 11].

The current work included an evaluation of crews' performance attending to their ability to bring the plant to a safe state in highly complex scenarios, targeting the design concept of the interface. As such, there is not a comparison between analog and digital interfaces or between computerized and paper procedures – this describes the development and proof of concept for a fully computerized control room interface. The paper is organized as follows: Section II describes a symptom check display designed to facilitate the monitoring of EOP entrance criteria as well as the main functionality and layout of the computer-based EOPs. Section III briefly describes a large screen display (LSD) specially aimed for emergency situations providing shared information viewable for all operators in the control room. Section IV presents the results from the initial testing of the computer-based EOPs in a full-scope simulator study.

II. THE COMPUTER-BASED EMERGENCY OPERATING PROCEDURES

The computer-based procedure system in HAMMLAB includes three displays: a symptom check display intended for the shift supervisor to monitor EOP entrance criteria; a procedure selection and overview display; and a procedure performance display. The procedure system automatically gathers dynamic information relevant to the procedure steps and highlights components and parameters to be checked or maneuvered, but does not provide automatic supervision of the plant state, nor execute pre-defined actions. The operators execute the prescribed tasks, sign the procedure steps electronically and can monitor team members' progress in other procedures. Earlier tests of the computer-based procedure system included procedures used after actuated reactor or turbine protection signals [12]. The current study investigated if the system could be extended to EOPs of flow chart type. The following chapters describe the displays in more detail.

II.A The Symptom Check Display

The EOPs are symptom based: When reactor scram is actuated or other unclear situations appear, the shift supervisor should check if any criteria for applying EOPs are met. A “Symptom check display” is supposed to facilitate this task. The symptom check display is organized into six areas, each presenting selected measurement values and status indications for a symptom. This information can be found in other displays, but is gathered in one display to save time and provide a better overview of the most relevant information for checking the EOP entrance criteria. For each symptom a button is provided to open the detailed EOP. A red frame appears around one or more of these buttons if criteria for using the EOPs are met. The symptom check display also presents important safety systems as well as detailed and redundant information to support operators’ decisions. Fig. 1 shows an example of the symptom check display four minutes after a large leakage inside the reactor containment has occurred and the main feed water pumps have stopped. Therefore two criteria for the use of EOPs are met: low water level in the reactor pressure vessel (RPV) and high pressure in the reactor containment.

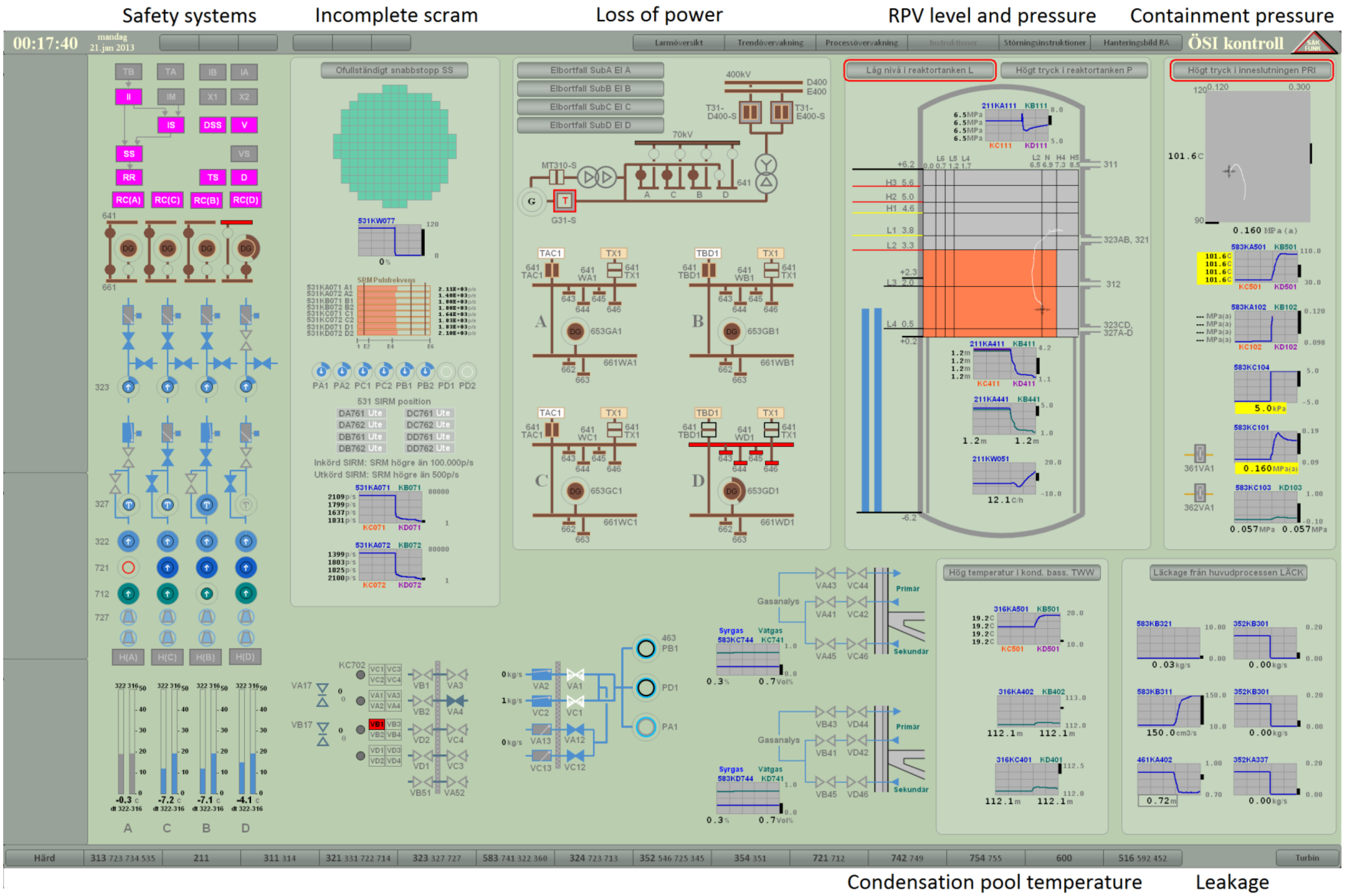

Fig. 1 shows the symptom check display when a large leakage inside the reactor containment has occurred. Two criteria for the use of EOPs are met: low water level in the RPV and high pressure in the reactor containment.

The status of the reactor protection system signals (RPS in magenta color when actuated) is shown in the upper left corner of Fig. 1, and below that the status of the most important safety systems (e.g., core cooling and heat removal systems). These safety systems are organized in four columns, one column for each subdivision (A, C, B, and D, see Fig. 1). The subdivisions are physically separated, and there are no connections between them. Normally the systems in the subdivisions are either on or off, so there is only one flow path. If there is more than one flow path it can be detected by checking which valves are open/closed. In some systems only the pump status and the flow are needed to check if the function is correct. The pie charts used in combination with pumps (indicating flow after the pump) make it possible to show the status of the safety systems after actuated RPS signals in a very small area and easily detect deviations. The status of the emergency diesel generators and the power produced are shown with the same principles above the safety systems and in the middle area of the display indicating power supply (see Fig. 1). From the symptom check display it is possible to see if diesel generators have started and if safety systems are powered from general power systems or diesel-backed bus-bars. Low voltage at a bus bar is indicated in red color. This visualization is used also in the large screen display (LSD) and other overview displays.

The symptoms are shown in priority order from left to right (In the future, the display could be reorganized in order to show all six areas in one line). The first symptom is “Incomplete scram”. At the top, the positions of all 169 control rods are shown. In this example all control rods are inserted by the hydraulic scram system and visualized in green color. If a control rod is not inserted it will be clearly visible by using white and/or red color.

Below the representation of the 169 control rods, different measurement values presented as digits, bar graphs and small trend graphs show the neutron flux (see Fig. 1). The trend graphs are auto-scaled to enable detection of small changes. Source and intermediate range monitors have movable detectors, and to ensure that correct values are shown the position of the detectors are indicated. The speeds of the eight recirculation pumps are also shown.

In Fig. 1 the symptom visualized in the middle of the display is “Loss of power”. All general and diesel backed bus bars, as well as connections to the national grids and the status of emergency diesel generators, are visible. Normal voltage is shown in brown color and low voltage is shown in red color. If diesel backed bus bars have low voltage in one subdivision the corresponding button will get a yellow frame indicating that the subdivision is not ok, but the operators decide whether to follow the relevant procedure or not. If two diesel backed bus bars from different subdivisions have low voltage the corresponding buttons will turn red and the operator should follow the procedures for one of the subdivisions.

There are two symptoms in the next part: “low water level in the RPV” and “high pressure in the RPV” (see Fig. 1). The water level is visualized by use of bar graphs, digits, small trends and an operating point that shows the water level and the pressure in the RPV in a combined diagram. The operating point is shown as a black cross with arrows in four directions. The average of the four wide range level and pressure measurements is used. If one of these signals deviates more than 10 % from the average the cross starts to flash, from white to black, to indicate that the operating point is not reliable. When the operating point moves a white history line is visible. The line shows the last 40 minutes. If the operating point reaches an alarm level the background color will change to yellow (reactor run back) or red (reactor scram). In addition to the operating point the pressure is shown as digits and small trends.

“High pressure in the reactor containment” is the symptom visualized in the right part of the display. Pressure and temperature are presented in digits, trends and an operating point that shows the temperature and the pressure in the containment in a combined diagram. The diagram is auto-scaled to make it possible to see small changes. The symptom “High temperature in the condensation pool” is shown as digits and trends. The water level is also presented. The last symptom is “Leakage from the main process”. Different sensors to detect a leakage are included by use of digits and trends. The shift supervisor should continuously monitor the symptoms and entrance criteria for applying EOPs until the plant has achieved a safe state, i.e., at least every 30 minute.

II.B The Procedure Selection and Overview Display

As shown in Fig. 2, the procedures are available through buttons grouped according to the operator roles in the left area of the Procedure Selection and Overview Display (PSOD). The active procedure in which the operator is currently working is indicated in white color. Blue color indicates that the procedure execution has been interrupted and not all steps are completed. Completed procedures are indicated in green. In a situation when a Reactor or Turbine Protection System (RPS/TPS) signal is actuated the reactor operator and turbine operator always start with the "first check" procedures to get a quick overview of the plant. These procedures are marked with a dotted red frame. The purpose is not to mitigate failures at this point, but report them to the shift supervisor, who will prioritize and distribute the tasks among the operators in the control room. The shift supervisor selects the EOP symptom check display to check if any criteria to follow EOPs are reached. The EOPs are opened either by pushing the buttons provided in the symptom check display, or by selecting the procedure in the PSOD.

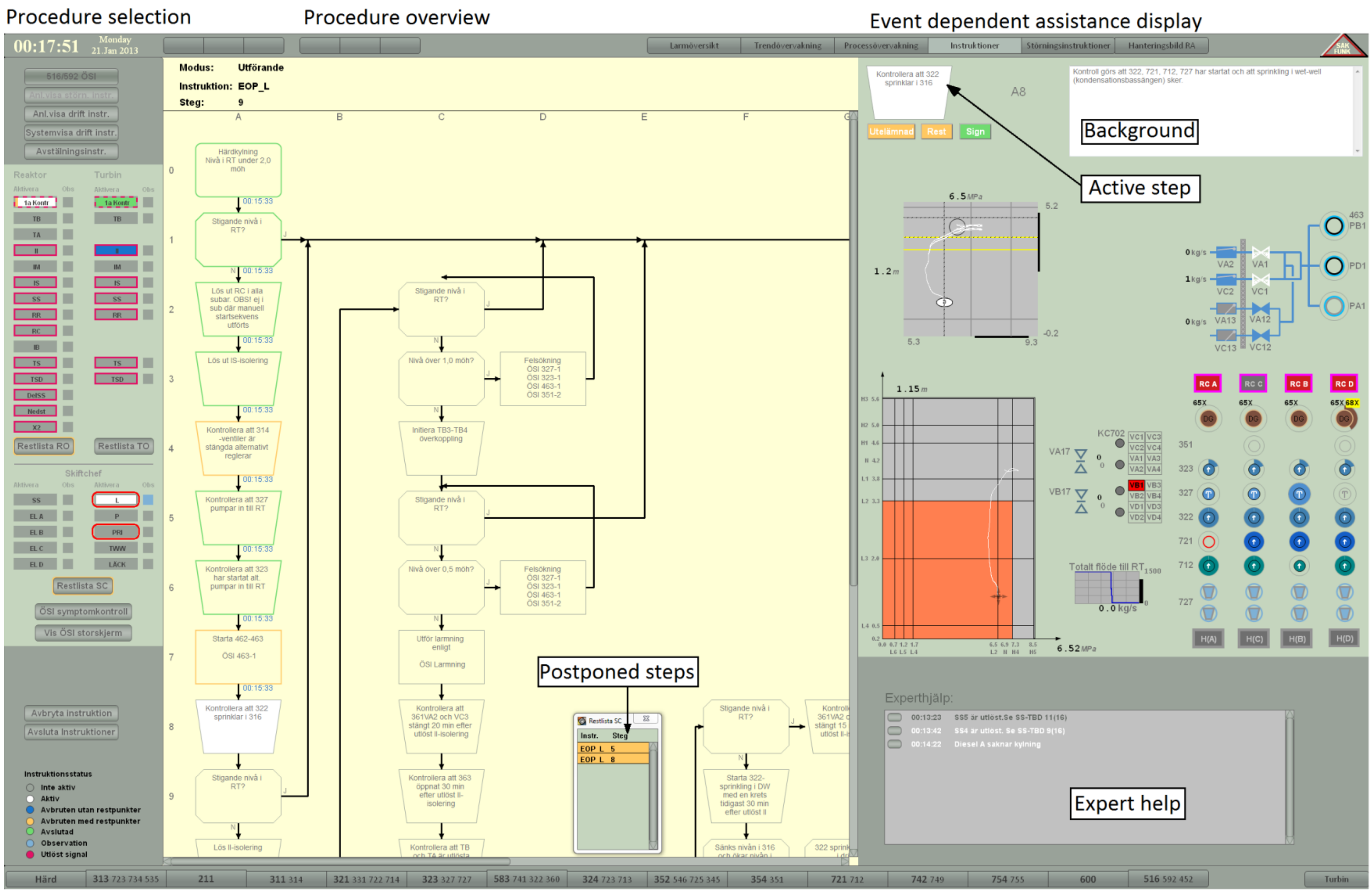

Fig. 2 shows the Procedure Selection and Overview Display (PSOD).

The procedures can also be opened in observation mode (read only) by selecting one of the smaller buttons to the right of the regular procedure selection buttons. The observation mode allows the operator to monitor the procedure overview in the PSOD and the execution of detailed procedure steps in the corresponding procedure performance display (PPD). For example, the reactor operator can select a procedure and execute the steps while the shift supervisor follows the progress of the reactor operator by selecting the procedure in observation mode at his/her workstation.

The selected EOP is presented as a flow chart in the yellow area, see Fig. 2. A set of shapes are applied to discriminate between the different types of steps such as manual operations (trapezoid shape), manual central and/or local operations where a special procedure is needed (rectangle shape) and yes/no questions (rounded rectangle shape, "yes" to the right and "no" downwards). The position of each step is defined by a coordinate to facilitate communication between the operators and track hand-written notes. White color indicates the active step, while the completed procedure steps have green outlines. If a procedure step cannot be performed or the operator detects a deviation, the procedure step should be marked as postponed. Postponed procedure steps are indicated by orange outlines. Similarly, an orange color on the button to select a procedure (in the left area of the display) indicates that one or more steps in the procedure are postponed. Postponed steps are listed separately for each operator. It is possible to navigate directly to a postponed step from these lists. The status of a step can be changed at any point, and the list of postponed steps is automatically updated. If a step is performed without deviations the operator presses the "Sign" button and the next step will appear. All work stations are continuously updated. Time stamps are recorded below the steps that are performed and postponed in the flow chart. In the future we also plan to enable written notes in the PSOD.

The operators may want to navigate between and execute multiple procedures in parallel. The procedure system records the progress of all procedures. When returning to a procedure that is not completed, the operator will be guided directly to the latest performed step. The operators can also navigate between steps in the procedure flow chart.

The most important information to monitor while performing a given EOP is made easily available in the right area of the PSOD, called the Event Dependent Assistance (EDA) display, see Fig. 2. The current procedure step and its background are presented on top of the EDA display. Below the procedure step indication, standard buttons for conducting the procedure work are provided, such as postpone and sign. While working in the EOPs, the operators also need to perform regular checks of parameters and status on components significant for the current situation and event. The dynamic process information is automatically gathered according to the selected procedure and the overall situation. For example, if there is a leakage from a pressurized system to the reactor containment, the operator would like to be continuously updated on the conditions in the reactor vessel, the containment, the status of the reactor protection system and safety components that are needed in this situation.

At the bottom, the "Expert help" (see Fig. 2) is a complement to the alarm system that provides decision support to the operators:

- Alerts the operators about critical conditions
- Alerts the operators about highly important alarms
- Provides timely guidance for required actions in accordance with the procedures
- Supports execution of particularly difficult tasks, for instance related to procedures.

II.C The Procedure Performance Display

Each procedure step has a pre-defined Procedure Performance Display (PPD) that automatically gathers the components, systems and parameters to be checked or maneuvered, see Fig. 3. The PPDs are usually the ordinary process displays available in the control room, but the PPDs can also combine information from multiple displays when needed. The design of the process displays is based on the P&IDs of the simulated plant. The plant parameters are shown as close as possible to their location in the plant. Large 30 inches screens are used which makes it possible to include several systems in the same display to show for example a complete cooling function. The intention is to reduce the navigation between displays as much as possible.

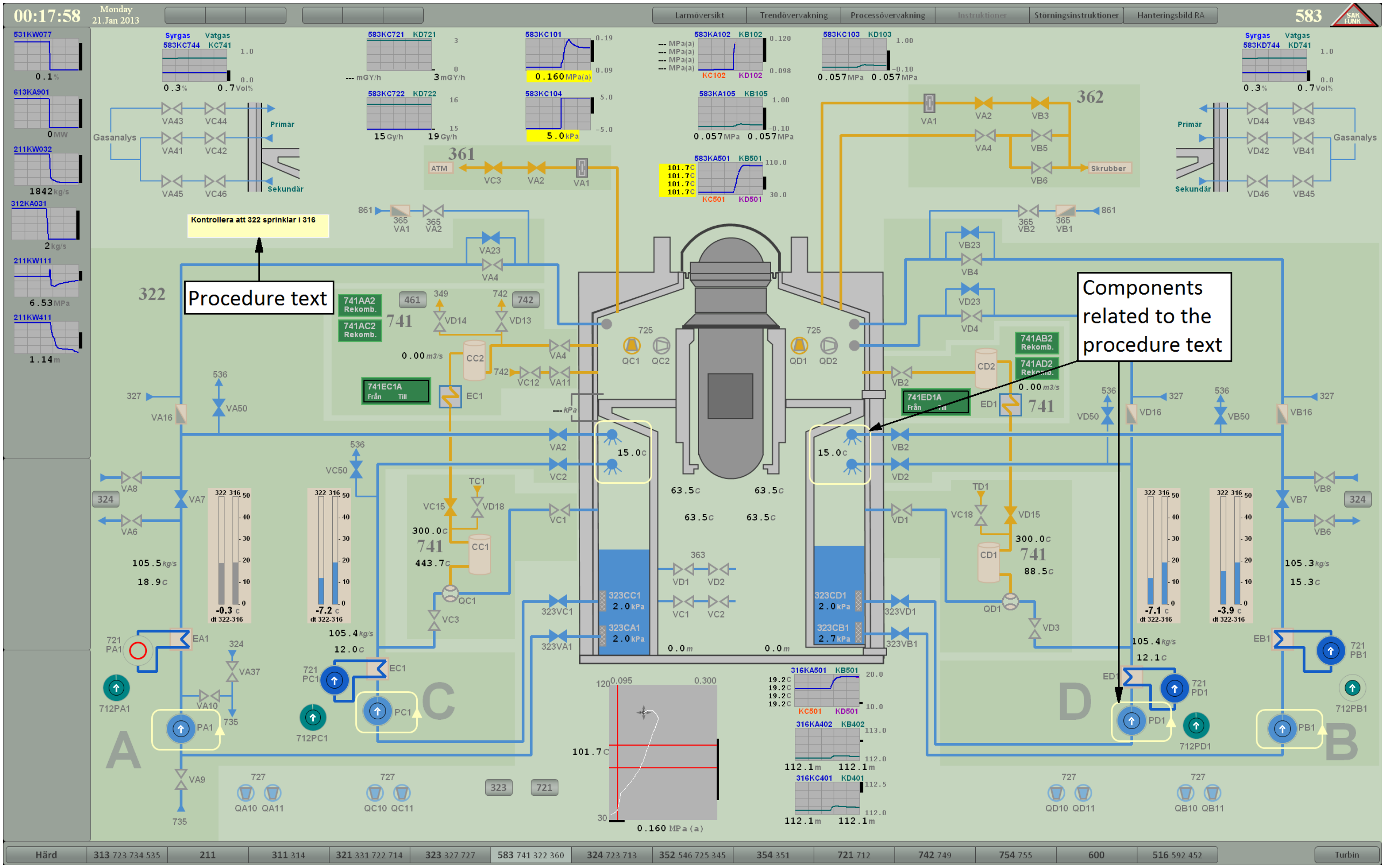

Fig. 3 shows an example of the Procedure Performance Display (PPD).

The step description is presented in a yellow text box as close as possible to the components without covering other information. The affected components or parameters are marked with a yellow frame, see Fig. 4.

Fig. 4 shows the frames identifying components or parameters to be maneuvered or checked. An arrow down to the left means stopping or closing a component. An arrow up to the right means starting or opening a component.

The computer-based EOPs are intended to be used as follows:

- Read the first procedure step provided in the flow chart within the PSOD.
- If needed, read the background information for the step.
- Identify the yellow frame(s) encircling the components or parameters to be checked or operated in the PPD.
- Perform actions in the PPD by clicking with the mouse on the component and use the control buttons that appear to perform the desired action (e.g., open or close a valve, start or stop a pump).
- When the manual actions or checks in the procedure step are completed and the effects of the actions are verified, press the green “Sign” button in the EDA display. The outline of the first shape in the PSOD flow chart turns green. The next step in the flow chart turns white, and the subsequent procedure step will appear in the PPD.
- If the step cannot be performed or should be postponed, press the Postpone (“Rest”) button. The outline of the step turns orange in the PSOD flow chart. The subsequent step turns white.

III. THE LARGE SCREEN DISPLAY FOR EMERGENCY OPERATION

The large screen display (LSD) provides shared information viewable for all operators in the control room (see Fig. 5A and Fig. 5B). The LSD is intended to be used for continuous monitoring during emergency situations together with the EOPs. In these situations the turbine area is not prioritized. The LSD presents the plant system in a less detailed way than the displays at the operator workstations. Colors and symbols are kept the same, and the layout of the systems is consistent across displays to avoid confusion. Some components have full designation, while other components have no designation according to the anticipated familiarity with components and risks of mistakes by the operators. The reason for partly omitting designations in the LSD is to reduce unnecessary clutter. The designation of a component consists of the system and component number, e.g. 312 VA1. 312 is the system number, VA1 is valve number. When a component can easily be related to a certain system, only the component number is shown, or the system number is indicated once for a group of components.

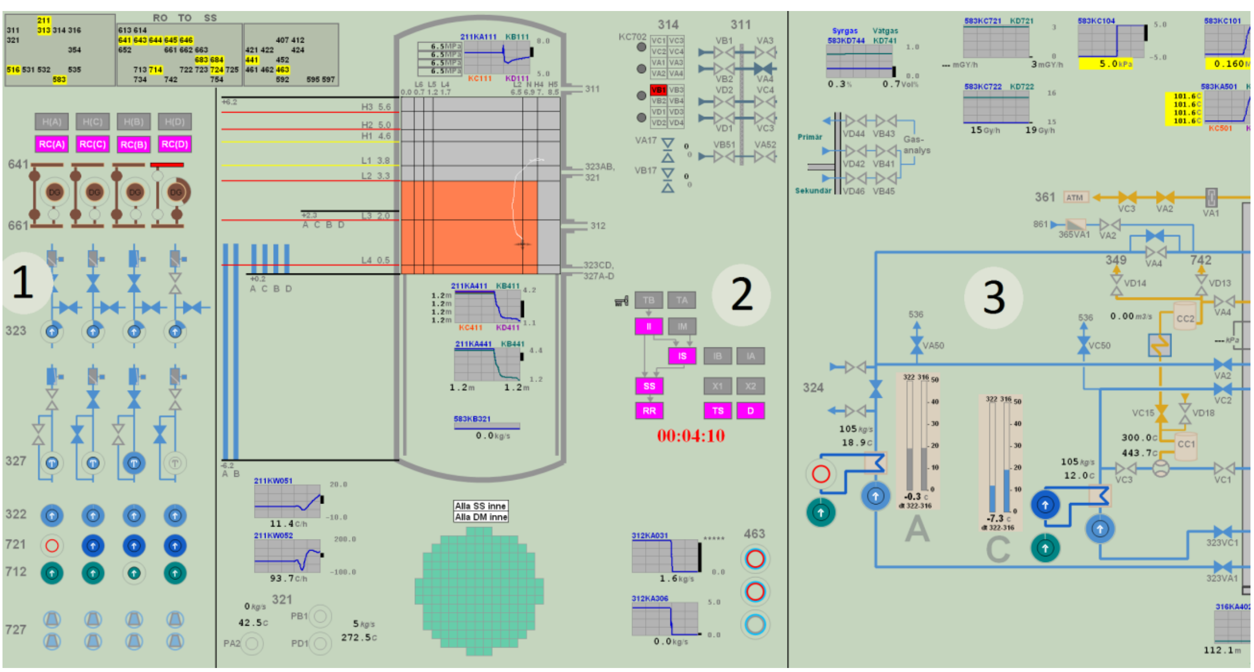

Fig. 5A shows the left part of the large screen display for emergency operation.

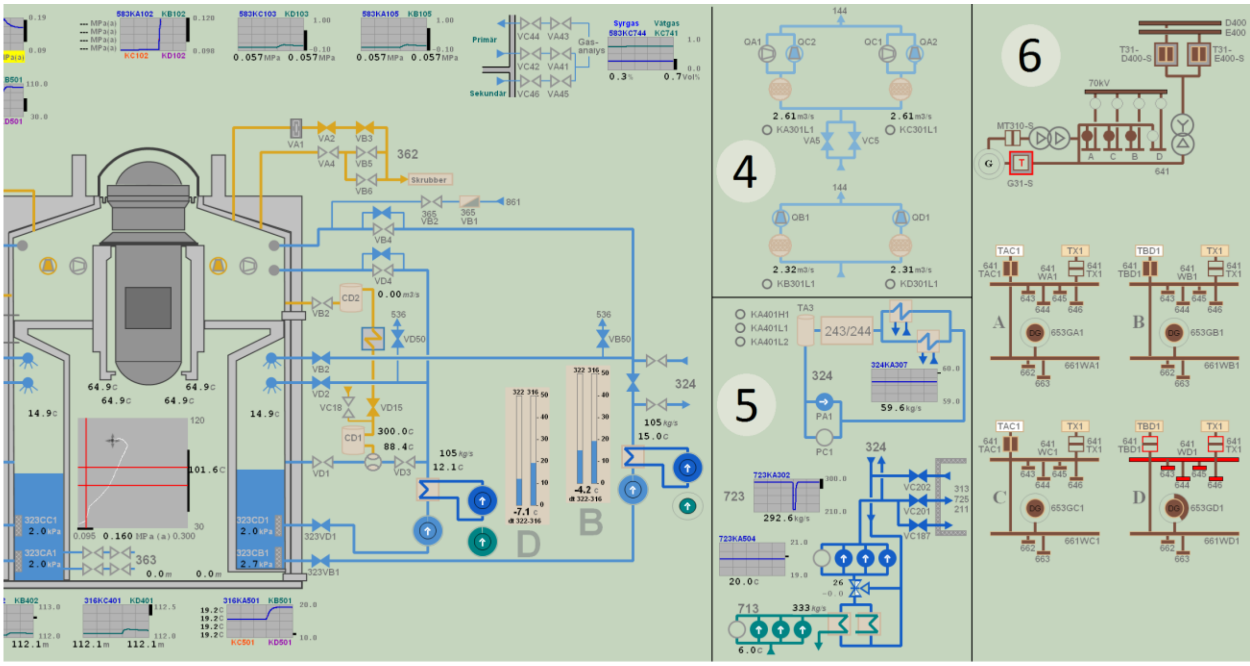

Fig. 5B shows the right part of the large screen display for emergency operation.

The LSD is divided into six parts, as illustrated in Fig. A and Fig. 5B above:

1. Overview of the important safety systems (described in II.A)
2. Status in the RPV, control rod positions, steam relief system, main feed water pumps, shut-down cooling system and status of the RPS and TPS
3. Containment instrumentation, gas treatment system, residual heat removal systems, reactor accident mitigation systems (over-pressurization protection system, containment filtered venting system, containment water filling system, system for water filling of the lower dry-well from the wet-well)
4. Reactor building emergency ventilation system
5. Spent fuel cooling systems
6. Power supply systems

IV. IMPLEMENTATION AND TESTING OF THE COMPUTER-BASED HMIS FOR EMERGENCY OPERATION

IV.A Implementation of the computer-based HMIs

We used a graphical user interface management system called ProcSee [13] to implement the computer-based HMI to the HAMlab BOiling water (HAMBO) simulator. ProcSee enables any aspect of the HMI to be linked dynamically to process parameter values from the simulator. HAMBO is a near full-scope simulator based on the Swedish nuclear power plant Forsmark unit 3. Forsmark unit 3 is a late generation ABB plant (BWR 75). At the real plant, the reactor and turbine systems are presented on panels and workstation desks. The plant computer provides simplified process displays, but the plant cannot be operated from this computer. In our simulator, we use the same signals that are available in the MCR at the simulated plant.

IV.B Initial testing of the computer-based procedure system and the LSD

The computer-based EOPs and the LSD for emergency operation were tested as a part of a larger study in HAMMLAB [14]. Three crews participated in the study. Each crew consisted of three licensed control room operators, representing one reactor operator, one turbine operator, and one shift supervisor in the study. Their mean age was 43.7 years and all were male. The crews were not from the simulated plant. They were provided four hours of training to familiarize with the simulated plant process and the various functions and features of the HMI.

The larger study included six scenarios, each lasting approximately 30-60 minutes. The purpose was to evaluate whether the integrated design concept supported safe operation based upon the acceptability of the observed human performance and how the different features supported the operators in detecting failures and deviations, diagnosing and mitigating disturbances. The scenarios covered a range of situations during start-up of the plant, disturbances and emergency operation. Five of the scenarios involved the use of computer-based EOPs. These were complex scenarios with high workload. Thus, the operators had limited time to inspect the PSODs and the LSD. We collected performance data through expert observations, operator self-ratings and direct assessments, i.e., questions to each operator about the current process state. The scenarios were audio and video recorded. After all scenarios were completed, the operators answered a usability questionnaire. They also provided individual written feedback on open-ended questions about the interface concept and discussed their experiences and opinions in a group interview. The main findings concerning the acceptability of the observed human performance and the usability of the computer-based EOPs and the LSD are summarized below.

IV.B.1 Expert ratings and video analyses of the human performance

A subject matter expert evaluated the performance of the crews during the scenarios. The expert evaluated the predefined behaviors on a six-point scale aimed at capturing the perceived acceptability of performance and control room systems [15]. The acceptability scale ranged from 1 (clearly not acceptable) to 6 (clearly acceptable). The instances of unacceptable performance were assessed consulting the video recordings.

Fig. 6 below shows a sub-set of the performance ratings for the five emergency scenarios that were specifically related to the use of the symptom check display, the computerized first check procedures and other computerized EOPs. All scenarios but one had average scores within the acceptable range (ratings superior to 4) – crew 3 got a borderline acceptability rating in scenario 5. The analysis of the video recordings showed that the operators in crew 3 had slow progress when performing the first check procedures in scenario 5. When these were completed and reported to the shift supervisor, the crew did not achieve a common understanding and strategy for mitigating the failures detected. We also observed the reactor operator searching for paper procedures although electronic procedures were available. In one instance, the reactor operator navigated in the electronic procedures for the turbine operator.

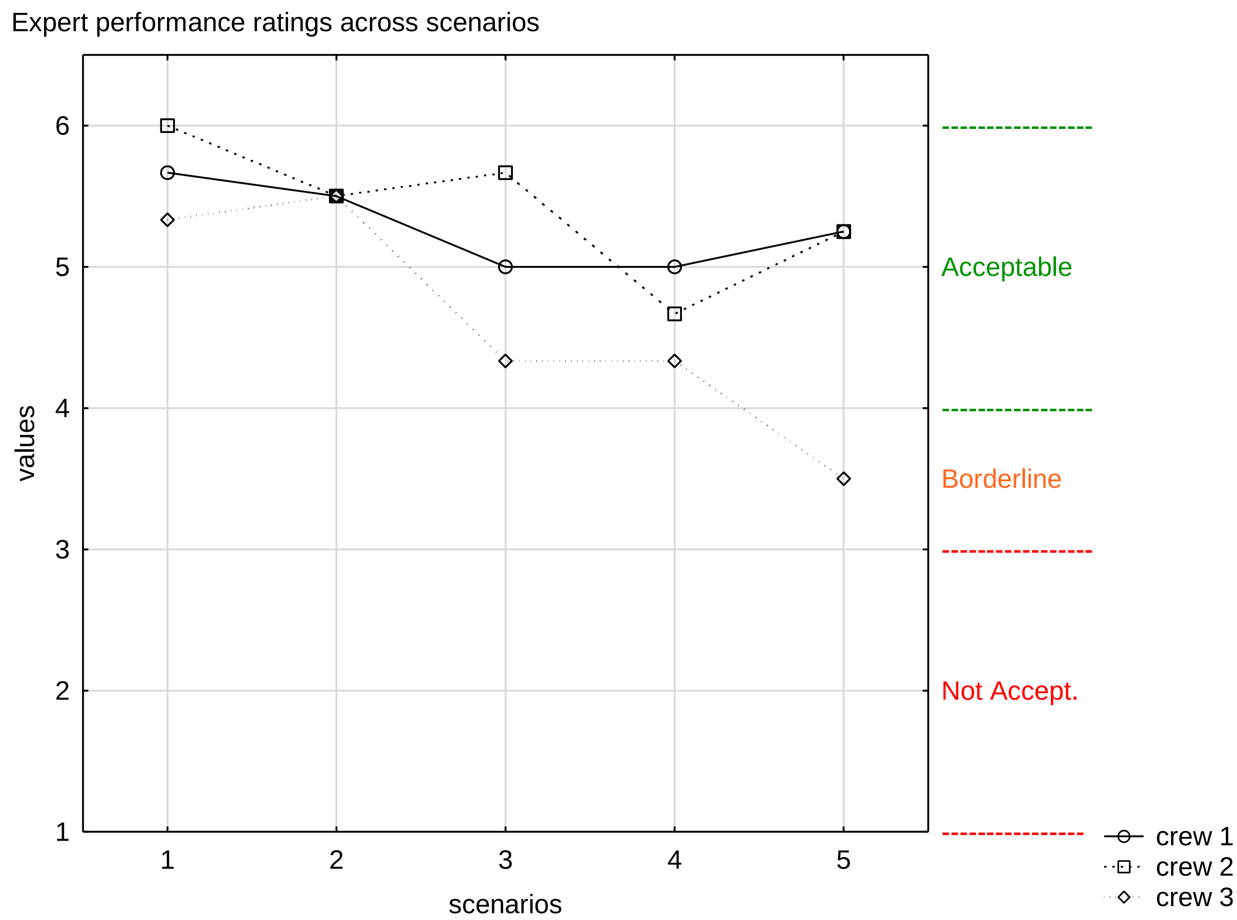

Fig. 6 shows the expert ratings of performance related to the use of the symptom check display and the computerized first check procedures across scenarios.

Altogether, the video analyses showed that most operators were able to select procedures and complete steps in the computerized procedure system without noticeable obstacles or delays in the five emergency scenarios. The event dependent information provided in the procedure system was utilized by some operators, while other operators preferred to use ordinary process displays and the LSD for emergency operation. We observed a few instances where operators navigated away from the computerized procedure to ordinary process displays in one computer, and later failed to open the procedure system from a second computer. The procedure system was available in only one computer for each operator workstation at a time.

IV.B.2 Usability ratings of the computer-based procedure system and the LSD

The usability questionnaire applied for the larger study had 46 items organized in four different sections: Alarm System (7 items); Large Screen Display (11 items); Computer-Based Procedures (14 items) and Workstation Displays (14 items). The items were developed specifically for a control room assessment setting and result from the adaptation of previous usability questionnaires and its integration with relevant usability topics taken from nuclear industry guidelines for HMI design [16]. As such, they reflect a set of statements on features that are generically considered necessary and/or desirable in a digital system (and are not directed to the actual features implemented in this design). Each of the items had to be rated by each of the individual operators in a scale from *1 – Non acceptable* (colored in red) to *6 – Acceptable* (colored in green). The intermediate scores were interpreted as borderline acceptable (average of 4), or borderline unacceptable (average of 3).

It is important to highlight a few limitations of the usability questionnaire regarding the current study: 1) the questionnaire was not designed specifically for this study – it is a generic usability questionnaire for control room application, which means that not all items were applicable to the current implementation of the HMI and not all specific features of the HMI were covered by the questionnaire; 2) the questionnaire was presented only once, after all scenarios had been completed, reflecting the overall evaluation of all computer-based procedures, and not exclusively the EOPs – that were used exclusively by the shift supervisors; 3) the presented ratings of the questionnaires represent the average rating provided by all participants in the study, not differentiating between operator roles and 4) the LSD ratings covered all scenarios, not referring only to the LSD specifically designed for emergency operations, but also including a LSD version used for normal operation.

All sections but the alarm section had an overall average within the acceptable range (rating superior to 4) – the alarm section showed a lower average, in the borderline rating. For the current purpose we will focus on the results regarding the Large Screen Display items and the Computer-Based Procedures. The specific ratings for the computer-based procedures section are shown in Fig. 7. In this section only 6 of the 13 items have average ratings above the borderline acceptable level. The items with the best ratings are item 4 “Indication of step completion” and item 5 “Indication of the current procedure step”, suggesting that the operators were satisfied with these features in the current implementation. Items 11 “Navigational links to reference material” and 13 “Indication of immediate required actions after a reactor trip” had the lowest scores in this section. As presented above, the nature of the presented system is different from the standard, since we are talking about a symptom based EOP system, where aspects such as priority of a step are not strictly defined since they will depend on the context – this aspect justifies the lower scores in items such as 1, 2, 6, 10, 11 or 13 since these features did not exist in the current system.

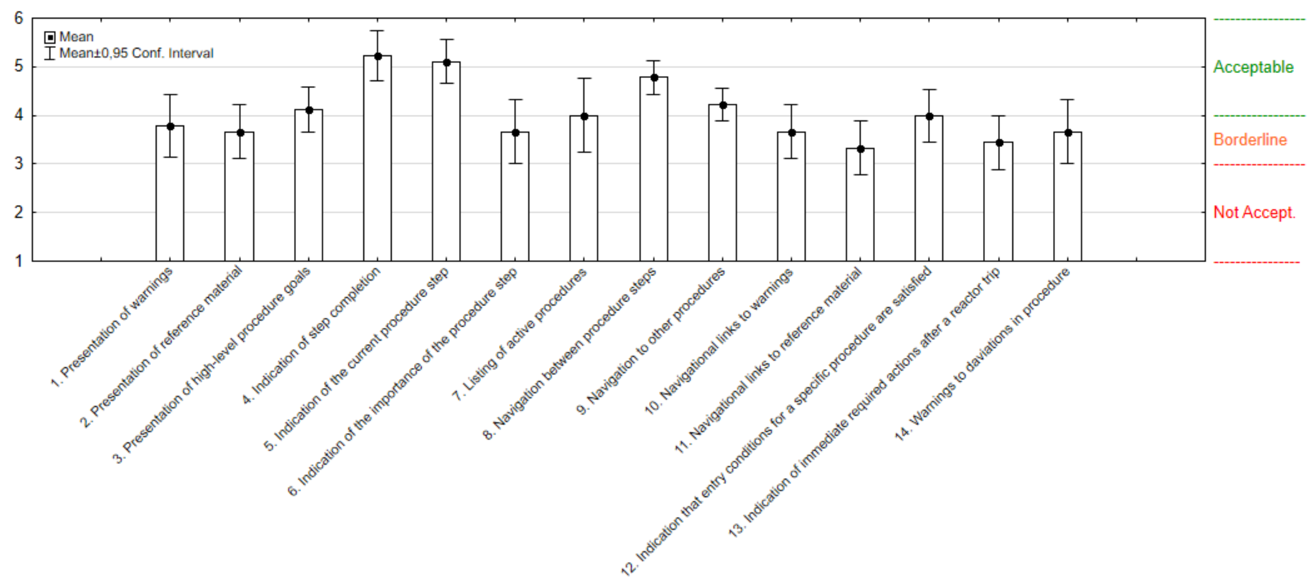

Fig. 7 shows the average usability ratings for the computer-based procedures items.

Fig. 8 shows the average ratings for the LSD questions. All items in this section are in the acceptable range (above 3). The item with the highest score average is item 4 “Overview of reactor level”, followed by item 3 “Overview of reactor pressure”, and item 8 “Overview of main circulation pumps”. On the other hand, item 11 “Overview of important alarms” got the lowest average score – this corresponds to a feature that is not incorporated in the current implementation of the LSD. Due to limited space in the current implementation, the presentation of the safety systems was prioritized above an overview of important alarms in the LSD. A list of unexpected alarms for the current plant state is included in a dedicated alarm display for the larger study. The lower rating presented by the operators reflects the need for further studies on presenting alarms in a manageable way when a large number of alarms are triggered in the control room.

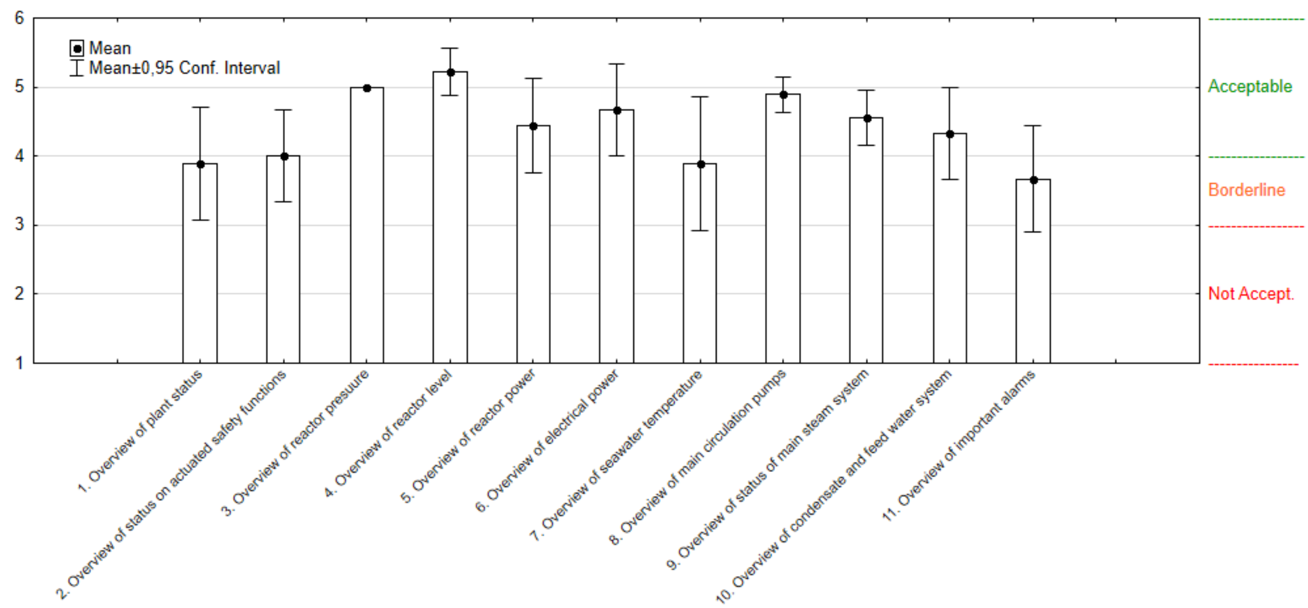

Fig. 8 shows the average usability ratings for the large screen display items.

An analysis of the ratings according to operator role showed that the shift supervisors had a more positive evaluation of the LSD than both the reactor and turbine operators, suggesting that the overview level of information was more useful for the shift supervisor. We can debate that the reactor and turbine operators would prefer a more detailed representation of the systems in the LSD, emphasizing alarm information that would be relevant to direct their actions. In emergency situations the LSD does not show turbine-specific information, maybe making the LSD less useful for the turbine operator and leading to lower ratings. Nonetheless, the purpose of the LSD was to provide a “at a glance” assessment of the plant status, which might be more interesting under normal operation than in the tested emergency situations that require specific actions and diagnostic procedures.

IV.B.3 Crew interviews about the usage of the computer-based procedures and the LSD

The three participating crews reported that the computer-based EOPs were feasible to use, and they highlighted the decision support provided in the symptom check display. The main advantages of the computer-based procedure system were the ease of access to the procedures needed, the automatic gathering of process information needed to perform the procedure steps, and the transparency between multiple operators working within the same procedure or in different procedures. The participants were able to identify and open the relevant procedures from the PSOD display. However, several participants reported that they would like to have dedicated screens for the computer-based procedure system. They wanted to keep their current view of process and trend displays side by side with the procedures. The test set-up had five screens available for each of the reactor and turbine operators, and four screens for the shift supervisor. Following the participants' suggestions, two additional screens would be needed for the procedure system in the reactor and turbine workstations, and three additional screens would be needed in the shift supervisor workstation.

The participants found the flow chart presenting the procedure steps easy to use. They experienced a good overview of the procedure progress indicated through color coding in the flow chart (active, completed or postponed steps). They easily kept track of where they or their colleagues were in the procedure, the burden of place-keeping being highly reduced compared to using paper procedures.

The extent to which the event dependent information presented in the right part of the PSOD display was used varied among the participants. Some participants stated that they used this actively, while other participants relied mainly on the large screen display for this process information. The "Expert help" was rarely used during the test. The automatic gathering of relevant process information in the PPD display was seen as a clear benefit of the system. This feature was of particular help to the participants in the study as they had limited HMI training and hands-on navigation experience. The frames identifying components or parameters to be maneuvered or checked made the procedure execution efficient. However, some participants raised a concern for complacency: Will the operators verify that they operate the correct component and detect if the system happens to highlight the wrong component?

The large screen display for emergencies was well received by the participating crews. They highlighted the advantage of having a common frame of reference and at-a-glance overview of the plant state in the early phases of an event. They especially appreciated the compact overview of the safety systems in the left part of the display (this section of the displays was not addressed by any specific item in the usability scale).

V. CONCLUSION

This paper presented the conceptual design of computer-based HMIs for emergency operation. The initial testing provided promising results, however further and more extensive training and testing would be needed to fully reveal the potential support and weaknesses associated with all the features exemplified in the implementation of the computer-based procedure system and the large screen display during emergencies. The planned next steps are to implement tracking of operator comments in the computer-based procedure system and make dedicated displays for the reactor and turbine operators' first check procedures in line with the symptom check display for the shift supervisor.

The computer-based HMI concept in HAMMLAB has been a knowledge-building activity within the Halden Reactor Project to provide ideas for improving information presentation in hybrid or fully computerized control rooms. In the upcoming research program we will investigate the typical design concepts for large screen overview displays used in existing nuclear control rooms and conduct controlled simulator experiments to assess the effects of these on human performance and operational safety.

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