HUMAN-MACHINE INTERFACE ASPECTS AND USE OF COMPUTER-BASED OPERATOR SUPPORT SYSTEMS IN CONTROL ROOM UPGRADES AND NEW CONTROL ROOM DESIGNS FOR NUCLEAR POWER PLANTS

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Abstract

Computer-based solutions for instrumentation and control systems replace old analogue equipment in nuclear power plant control rooms and CRT-based human-computer interfaces replace conventional control and instrument panels. At the same time designs for tomorrow's reactors are developed characterized by fully digital instrumentation and control systems, and advanced, computer-based control rooms. These trends open possibilities for improving the support functions assisting operators in their cognitive tasks. At the Halden Project efforts are made to explore these possibilities through design, development and validation of Computer-based Operator Support Systems (COSSes) which can assist the operators in different operational situations, ranging from normal operation to disturbance and accident conditions. The programme comprises four main activities: 1) verification and validation of safety critical software systems, 2) man-machine interaction research emphasizing improvements in man-machine interfaces on the basis of human factors studies, 3) computerized operator support systems assisting the operator in fault detection/diagnosis and planning of control actions, and 4) control room development providing a basis for retrofitting of existing control rooms and for the design of advanced concepts. The paper presents the status of this development programme, including descriptions of specific operator support functions implemented in the simulator-based, experimental control room at Halden (HAMMLAB, HAlden Man-Machine LABoratory). These operator aids comprise advanced alarms systems, diagnostic support functions, electronic procedures, critical safety function surveillance and accident management support systems. The different operator support systems developed at the Halden Project are tested and evaluated in HAMMLAB with operators from the Halden Reactor, and occasionally from commercial NPPs, as test subjects. These evaluations provide data on the merits of different operator support systems in an advanced control room setting, as well as on how such systems should be integrated to enhance operator performance. The paper discusses these aspects and the role of computerized operator support systems in plant operation based on the experience from this work at the Halden Project.

1. INTRODUCTION

Even if nuclear power plants have a very good safety record, there is a strong motivation in all countries for further improvements. Control room improvement is given high priority, and modern computer technology, used in the correct manner, has the potential of greatly improving operational safety.

A number of weaknesses in old control rooms have been identified: relevant information may be missing due to limited instrumentation, too much information (alarms) may make it difficult for the operator to diagnose the process state, wrong or inconsistent information may mislead the operator. In addition, the operator could benefit from assistance in both diagnosis of problems, in action planning and in implementation of control actions.

Techniques are available to improve on all points given above: dynamic process models may supply relevant process information, alarms may be filtered and presented more clearly and well structured, consistency check of process data before presentation helps identify wrong measurements. Knowledge-based or model-based operator support systems may diagnose the cause of plant disturbance and identify which procedures are relevant. Finally, computerized procedures may prevent the introduction of errors that often are experienced.

At the Halden Project efforts are made to explore these possibilities through design, development and validation of Computer-based Operator Support Systems (COSSes) which can assist the operators in different operational situations, ranging from normal operation to disturbance and accident conditions.

These systems are implemented in the simulator-based, experimental control room at Halden (HAMMLAB), where they are tested and evaluated with operators from the Halden Reactor, and in some cases also with operators from the Loviisa NPP in Finland, as test subjects. Through these experiments data on the merits of different operator support systems in an advanced control room setting are obtained. Further, studies of how the systems should be integrated in the existing control room to provide efficient operator support are carried out. Adding new COSSes may increase the information in the control room, resulting in increased danger of information overflow, if information structuring and presentation are not properly designed. The man-machine interface of the COSSes should be standardized, and care must be taken to avoid that the operator is so involved in the use of one particular COSS that he overlooks more important tasks to be performed.

This paper gives an overview of the man-machine systems research and a brief description of a number of the COSSes developed at the Halden Project, and discusses aspects of system evaluation and integration before such systems are taken into use in plant operation.

2. MAN-MACHINE SYSTEMS RESEARCH AT THE HALDEN PROJECT

The research programme at the Halden Project addresses the research needs of the nuclear industry in connection with introduction of digital I&C systems in NPPs. The programme provides information supporting design and licensing of upgraded, computer-based control room systems, and demonstrates the benefits of such systems through validation experiments in Halden's experimental research facility, HAMMLAB and pilot installations in NPPs.

The programme includes four main areas: 1) verification and validation, 2) man-machine interaction research, 3) computerised operator support systems, and 4) control room development. Fig. 1 illustrates how these areas are interconnected and also shows the type of deliverables from the different areas.

The activity on *verification and validation* addresses software safety and reliability aspects. The work comprises investigations of methods and tools which can be used to improve the reliability and verify the safe use of computerised control and supervision systems for nuclear power plants. The results provide a basis for establishing guidelines for design and licensing of safety related software.

The work in the *man-machine interaction* area aims at enhancing safe and efficient operation of nuclear power plants through improving the man-machine interfaces of the control room systems based on human factors considerations. To this end experimental evaluation of the systems is performed in HAMMLAB using operators from the Halden Reactor as test subjects. In addition to improving the man-machine interface of the specific operator support systems being developed at Halden, the analyses of these validation experiments provide a more general understanding of factors influencing operator behaviour. This knowledge is utilised to establish technical bases for guidelines for design and evaluation of man-machine interfaces.

The work on *computerised operator support systems* addresses development of systems assisting the operator in functions like fault detection, diagnosis and prognosis, and advisory systems aiding him in action planning and implementation. The work in this area is primarily aimed at developing systems for backfitting in current control rooms, but the resulting systems are also applicable as modules within more integrated surveillance and control systems in advanced control rooms.

The activity in *control room development* addresses the potentials and possible problems of completely computer-based control rooms including several operator support systems. The work comprises integration of these systems focusing on co-ordination and prioritisation of information, man-machine interfaces and underlying hardware/software structures. A demonstration version of a fully digital control room is established in HAMMLAB. This demonstration control room is utilised to gather information of relevance for the introduction of digital control room solutions in nuclear power plants.

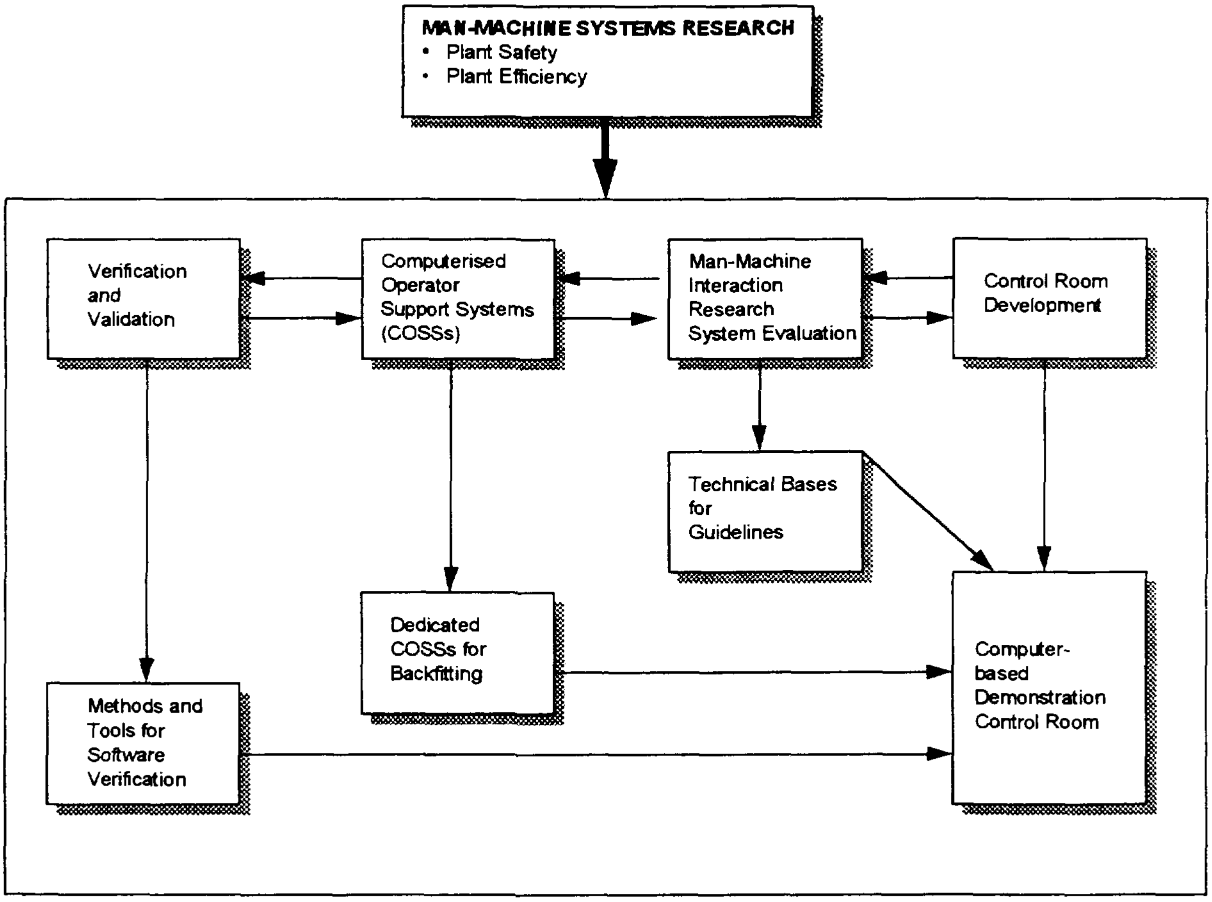

FIG. 1. Man-Machine Systems Research Programme. Upper four boxes show the four main programme items, lower four shows the main products from the research programme at Halden.

3. COMPUTER-BASED OPERATOR SUPPORT SYSTEMS DEVELOPED AT THE HALDEN PROJECT

5.1. Model-based early fault detection

Early detection of faults and plant disturbances in nuclear power plants reduces the risk of disturbances developing into severe plant conditions (shutdown or accidents) since the operators have more time for diagnosis and counteractions. Further, early detection of the disturbance usually means better localisation of the problem area in the plant, thereby facilitating the diagnostic task. The traditional way of informing operators about possible problems is through alarm systems based on limit checking of process variables, which should stay within prescribed limits. In many cases a disturbance in a plant subsystem may propagate into neighbouring subsystems before the operator is alerted by the alarm systems. Therefore, the operator is confronted with a large number of alarms within a short period of time which makes the diagnostic task difficult. Alarm filtering techniques may reduce this problem to some extent by focusing on essential alarms [1].

An alternative method for fault detection is illustrated in Fig. 2. The method is based on mathematical reference models describing the dynamic behaviour of the process in normal operating conditions (no disturbances or faults in the process). By comparing measured process variables with corresponding calculated variables from the reference models in real-time, the time to detect disturbances can be reduced compared to traditional alarm systems. By splitting the reference models into a number of submodels where the input variables to each individual submodel are measured output variables from the preceding subprocess (Fig. 2), a good localisation of the problem area in the plant is obtained. By this technique, propagation of faults in the detection algorithms outside the particular subsystem containing the fault, is avoided thus reducing the diagnostic task [2]. However, also this method requires additional rules for detailed diagnosis in order to discriminate among various possible failures within a subsystem which may cause an observed deviation between reference models and measurements. For instance, errors in the control system or instrumentation may turn out to be the real problem, but this type of failure should also be detected as early as possible.

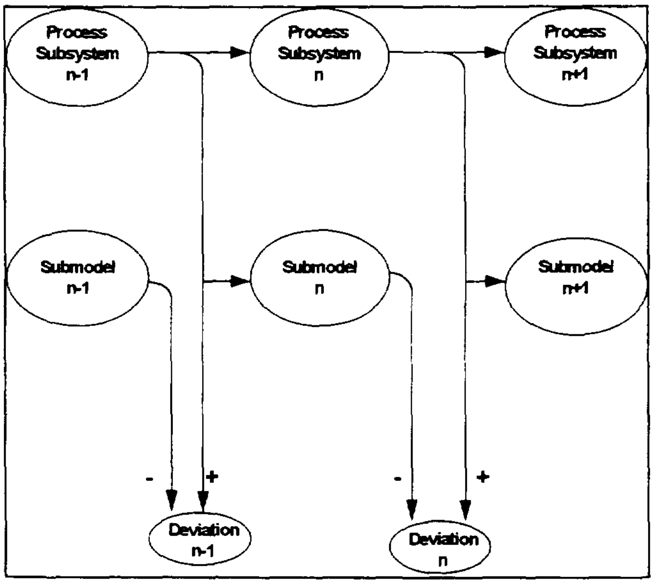

FIG. 2. The principle of model-based early fault detection.

At the Halden Project Early Fault Detection (EFD) systems based on the method described above have been developed. Two pilot installations have been made at the Loviisa nuclear power plants in Finland, one for leakage detection and one for signal validation of flow sensors. The systems have proved successful through detecting internal leakages in preheaters in the feedwater system and degradation of feedwater flow instruments [3,4].

5.2. Surveillance of critical safety functions

In case of major disturbances in nuclear power plants which may develop into severe accident situations, traditional event-oriented alarm systems may not provide sufficient assistance to the operators. This is partly due to the fact that these kind of systems may fail to draw operator attention to the important problems in the plant. An event-oriented, limit checking system leads to a large amount of alarm messages even in situations where you have a moderate plant disturbance. The presentation of unimportant information mixed with important information may in fact be misleading to the operator. Further, an event-oriented alarm system tends to draw the operator's attention to problems with individual components while his attention in accident situations rather should be directed towards the performance of critical plant functions.

These problems have resulted in a function-oriented approach to nuclear power plant monitoring for disturbances which potentially may develop into accidents. From systematic studies of scenarios that may lead to accidents a set of critical safety functions is defined. These functions have to be maintained to prevent serious consequences of the disturbance, like staff injuries and plant damage.

This function-oriented approach to plant monitoring has lead to development of so-called Safety Parameter Display Systems (SPDSs, also denoted Critical Function Monitoring Systems) which alarm the operators when critical safety functions are threatened. The emergency operating procedures (EOPs) have been restructured accordingly, the EOPs of nuclear power plants are now all symptom-based (i.e. function oriented) and aim at checking the status and maintaining the integrity of the critical safety functions.

The Halden Project has explored the concept of critical safety function monitoring through development and evaluation of different SPDS-types of systems. Together with Combustion Engineering the Halden Project evaluated the Critical Function Monitoring System (CFMS)(and the Success Path Monitoring System (SPMS) in HAMMLAB [5]. The SPMS system augments the monitoring of the critical safety functions through presenting to the operator the status of alternative success paths for maintaining a particular critical function in case it is threatened or lost. The experiments in

HAMMLAB showed clear advantageous effects of supporting the operator with success path monitoring with respect to his performance during simulated accident scenarios .

5.3. Intelligent alarm handling

One of the main tasks for operators in nuclear power plants is to identify the status of the process when unexpected or unplanned situations occur. The alarm system is the main information source to detect disturbances in the process, and alarm handling has received much attention after the TMI accident in 1979. It was realized that conventional alarm systems created cognitive overload for the operators during heavy transients.

Over the years the Halden Project has explored different approaches to alarm handling, like alarm filtering techniques, model-based early fault detection and function oriented approaches like critical safety function monitoring.

The experience gained from the work with these different alarm systems has shown that there is a need for a generic tool for configuring more intelligent alarm systems where different alarm handling techniques can be integrated. Therefore, the Halden Project has developed an alarm system toolbox, called COAST, which makes it possible to build integrated alarm systems through mechanisms for addressing different principles for alarm generation, structuring and presentation [6].

COAST contains facilities for building specific alarm systems as well as facilities for alarm system execution. It is an integral part of the final alarm system, and is not only a tool for building dedicated systems. COAST is shown in its final environment in Fig. 3.

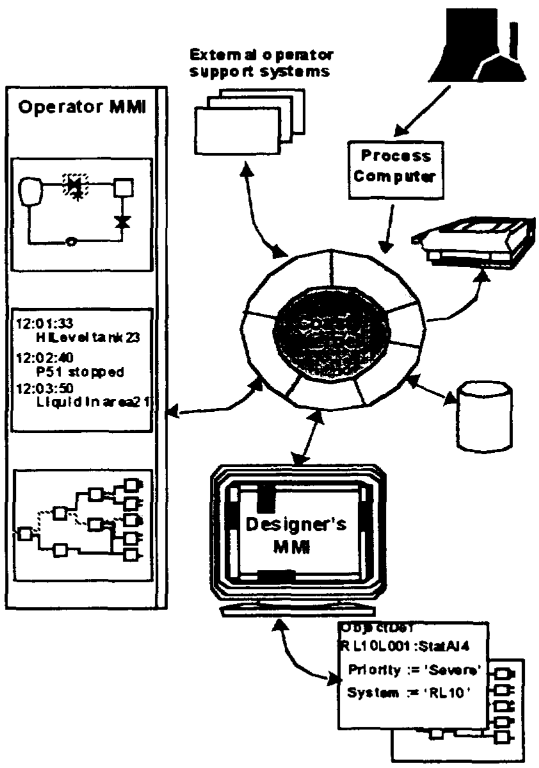

FIG. 3 The COmputerised Alarm System Toolbox, COAST, with interfaces to external systems

COAST is meant to be an add-on possibility to conventional process control systems. As shown in Fig. 3, it receives process measurements from the process computer, updates all necessary statuses, and sends updated alarm information to the display system in the control room. COAST itself does not possess graphic capabilities, but can easily be coupled to different graphical systems. It has been coupled to the Picasso-3 user interface management system developed in Halden [7]. Coupling to all external systems is done through an application programmer's interface, which includes simple functions to get data in and out of COAST, e.g., process data must be provided as input to the alarm objects. It is also easy to couple COAST to an existing alarm system. Existing alarms will then be structured or filtered by COAST before presentation. The designer's MMI is designed as an alarm editor, but it is also possible to operate COAST through text-files.

An advanced alarm system called CASH (Computerized Alarm System for HAMMLAB) [8] has been developed using the COAST alarm system toolbox and installed and tested in the PWR simulator-based experimental control room at Halden. New methods for alarm structuring and presentation are introduced, which together with established ones provide a high degree of suppression of non-important alarms. CASH introduces an innovative overview display which combines advantages of space-distributed tile alarm systems and CRT based systems with chronological alarm list. No information is removed from the system, only suppressed from the overview display according to well-defined criteria. However, all alarms and additional information are available upon request in so-called selective displays. Alarm information is also integrated into process mimics displays used for process control and surveillance.

5.4. Diagnosis systems

At the Halden Project prototypes of diagnostic systems have been developed to investigate their merits for NPP operation. DISKET is a rule-based expert system where information on patterns of the actual alarms and other process variables are matched with precalculated patterns from known disturbances to arrive at hypotheses for the cause of the alarms. The system was originally developed by JAERI (Japan) and further developed at Halden. DISKET has been validated in HAMMLAB, and the results show improved operator performance when the operators have access to DISKET during disturbances [9].

Detailed Diagnosis (DD) has been developed to perform diagnosis of alarms originating from the Early Fault Detection (EFD) system. The diagnosis is based on knowledge based techniques. Typically the results will be identification of failed components, control system failure or instrument malfunctions.

Currently the Halden Project is working on an Integrated Diagnosis System aiming at utilisation of the experience from already developed diagnosis systems to make a general framework for diagnostic systems, incorporating important qualities of the previously developed systems. In this way, more robust systems will be obtainable due to the diversity in diagnostic methods and knowledge [10].

5.5. Computerized procedure system

A number of observed and potential problems in the nuclear industry is related to the quality of operating procedures. Especially when it comes to EOPs, much work has been done in recent years for improving their quality. This applies to most aspects related to procedure production, procedure structure and contents, procedure implementation and procedure maintenance.

Many of the problems identified can be directly addressed by developing COmputerised procedure handling tools. Thus, there is a growing interest in taking modern computer technology into use for improving today's practice in procedure preparation, implementation and maintenance.

COPMA-II is a computerized procedure system developed at the Halden Project [11]. The system has two main components: *the procedure editor, PED-II*, is a tool designed to be used by the procedure writers during procedure preparation and procedure maintenance. Procedures to be used with COPMA-II must be expressed in a formal, general purpose procedure language, PROLA, developed by the Halden Project. *The COPMA-II On-line procedure following system* is the tool developed for supporting the process operators during retrieval and execution of procedures. The term *on-line* reflects that the system is designed to work with a live data communication link to the process computer, simulator, or any other external software component. Fig. 4 illustrates the relationship between PED-II, COPMA-II On-line and the plant computer or simulator.

COPMA-II is intended to *replace* the traditional system of paper-based procedures. Existing hard-copy procedures must be transferred to COPMA-II by using the procedure editor. A more or less thorough rewriting of the procedure using the PROLA procedure language is necessary. There are *no* elements of automatic procedure generation or procedure synthesis during on-line operation.

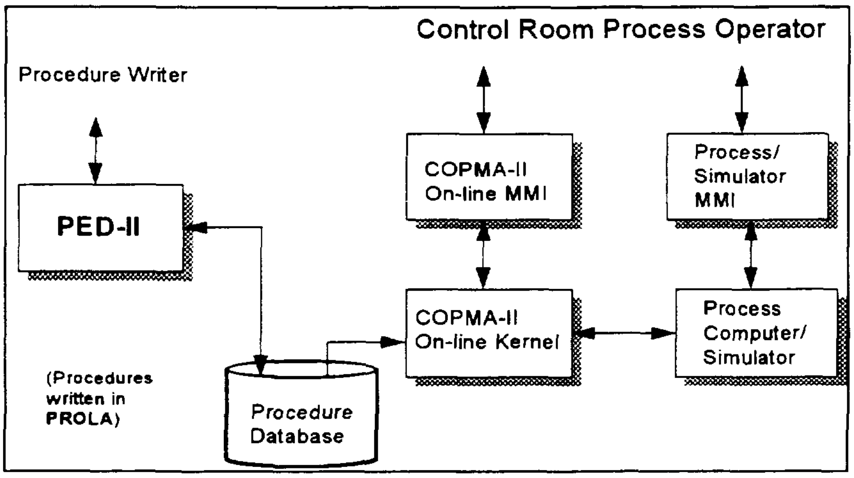

FIG. 4. COPMA-II system components.

COPMA-II acts as a *shell* for storing procedural information, for access and implementation by the operating crew. As designed, COPMA-II is not supposed to automate the actual execution of procedures. Normally, the operator drives the execution by acknowledging individual instructions within the procedure, making his personal judgments as much as he did when using hard-copy procedures. COPMA-II may also, if permitted to do so, act as a partial control interface to the process, because certain actions specified in the procedures can be carried out directly through the COPMA-II On-line user interface. The integrated information available in COPMA-II combined with the support functions offered by the system, is intended to improve operator performance when implementing operating procedures compared to when doing the same job with paper procedures.

COPMA has been subjected to human factors evaluation experiments in HAMMLAB using Halden Reactor operators as test subjects and at the Scaled Pressurized Water Reactor Facility at North Carolina State University where 16 licensed NPP operators were test subjects. These studies have shown that operators can increase their performance and reduce their error rates when using COPMA, compared to using paper-based procedures.

5.6. Computerized accident management support

The Halden Project is carrying out a research programme on Computerized Accident Management Support (CAMS). The aim is to establish a prototype of a system which can provide support to the control room operators and the staff in the Technical Support Centre during accident situations. The CAMS prototype utilises available simulator codes and the capabilities of computer-based tools to assist in identification of plant state, prediction of future development of the accident, and planning of accident mitigation strategies [12,13].

The CAMS prototype consists of a signal validation module, a tracking-mode simulator, a state identification module, a predictive simulator, a strategy generator, a PSA risk monitor, and a man-machine interface system, see Fig. 5.

The signal validation module utilises neural networks techniques. The tracking-mode simulator will be used to support signal validation and for state estimation. There are a lot of physical quantities that cannot be measured. If there is enough data available, they can still be calculated. The tracking-mode simulator is supposed to take care of that.

The predictive simulator predicts what will happen in the plant in the future. The future will depend not only of the present state, but also of the planned control actions. Many situations with different control actions can be tested, as well as the proposals from the strategy generator and from the users.

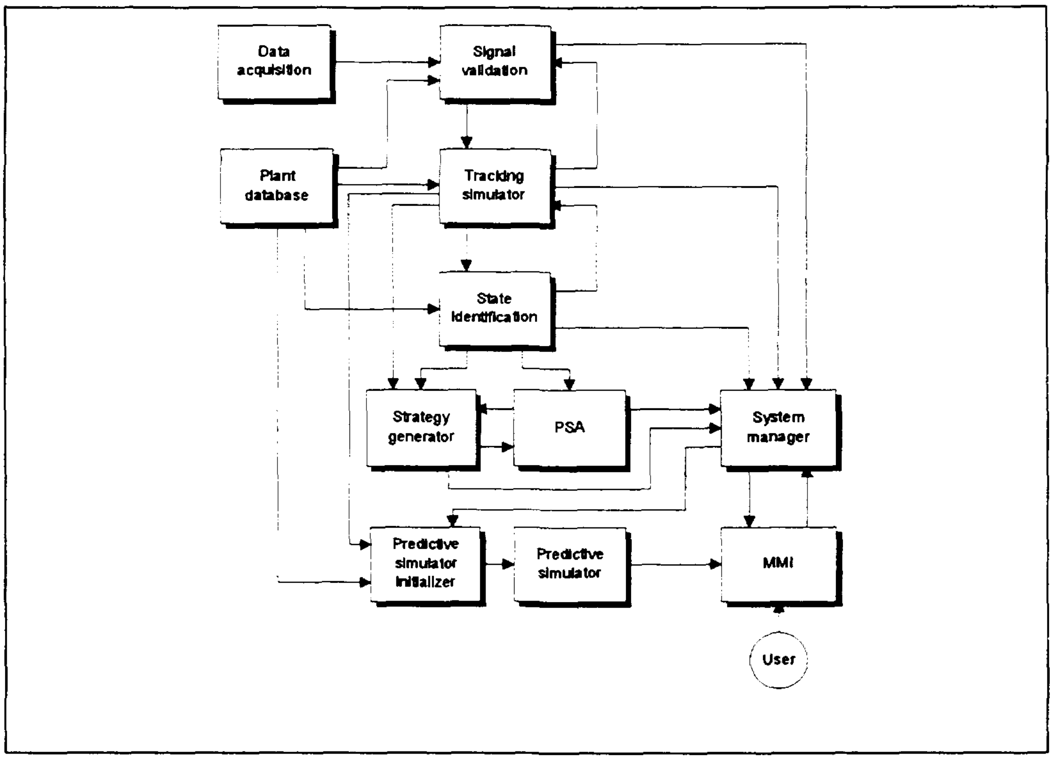

FIG. 5. Block diagram of the CAMS system.

The strategy generator shall provide control proposals and accident mitigation strategies to operators, shift leaders and to the staff of the technical control centre. A PSA module is used for risk monitoring taking into account the current state of the plant.

The users interact with the system through the man-machine interface. Much work is devoted to finding what information to display in different situations and how this information shall be represented.

A first prototype of CAMS comprising the predictive capabilities has been developed, and was tested in a safety exercise in Sweden in co-operation with the Swedish Nuclear Inspectorate (SKI). The test illustrated the potentials of a system like CAMS for accident management training.

5.7. User interface management systems

User Interface Management Systems (UIMSs) are tools to realise graphic user interfaces (GUIs), i.e., presentation of dynamic process information and handling of operator dialogues. The Picasso system is a UIMS tool developed at the Halden Project which is used in development of the GUIs of most of the COSSs described in this paper.

The latest version, Picasso-3, supports object-oriented definitions of GUIs in a distributed computing environment. The system comprises an interactive graphic editor for drawing pictures, generating class libraries and dialogues, and a C++ inspired programming language for defining advanced picture dynamics [7].

4. EVALUATION OF COMPUTER-BASED OPERATOR SUPPORT SYSTEMS

The development of COSSes at the Halden Project has clearly shown the potentials for improved plant operation through taking more advanced operator aids into use. However, introduction of these systems in a NPP control room requires that the systems are thoroughly evaluated with respect to the impact on operator role and performance. The essential role of the operator is to maintain the safety of the plant. Since COSSes obviously have the capability to effectively change some aspects of the role of the operator, we must carefully consider whether such changes are desirable. Further, as improvements in overall performance of the operator crew is the objective of developing and introducing COSSes in the control room, a continuous evaluation must be performed during design and implementation of these systems to assure that this objective is met.

The Halden Project is engaged in defining measurable objectives for operator support systems to enable experimental validation of specific operator aids. Although an ideal way to validate systems might be to measure real operator performance in the actual control room situation, this is not feasible because appropriate incidents for system testing are fortunately rare (or not occurring) in real plants. The most realistic way to validate the COSSes are thus evaluation in a full-scale simulator, where real conditions should be simulated as accurately as possible. All COSSes developed at Halden is validated in this way through experiments in HAMMLAB where operators from the Halden Reactor or occasionally from the Loviisa NPP in Finland are taking part as test subjects. In some cases experiments in HAMMLAB are supplemented with experiments in training simulators of member organizations of the Halden Project, to provide additional data, e.g., comparisons between conventional and more advanced control room settings. Over the years a broad spectrum of evaluation methods has been developed and enhanced to observe and validate human factors characteristics of the COSSes in a best possible way. Important factors which must be considered are system user (operator, shift supervisor, technical support centre), workload, automation degree (allocation of task to system or operator), operators' situation awareness, information load, information separation (separate events clearly distinguishable), etc.

In addition to providing design feedback on a specific COSS, the evaluations also provide more generic data of importance for formulation of guidelines for man-machine systems design. In order to facilitate this work the experience from the system evaluations at Halden has been collected and summarized in lessons-learned reports [14].

In advanced, fully-digital control rooms the possibility exists for integration of a number of different operator support functions. This poses a special challenge, namely that of proper co-ordination of the different functions. One must avoid that the operator is so involved in the use of one COSS that he overlooks more pressing problems when they occur. The control room must be conceived as a balanced entity, not as a collection of COSSes.

A set of requirements follow from this: a top-down design taking care of the co-ordination and prioritization of different tasks and functions must be followed. Further, a unified, standardized man-machine interface including all COSS functions must be designed. At the Halden Project a prototype of such an integrated solution to an advanced control room comprising eight different COSSes has been developed and thoroughly evaluated in operator experiments [15], providing useful information for design and implementation of this kind of control rooms.

5. CONCLUSIONS

The upgrading of NPP control rooms with introduction of new plant computers and digital I&C systems opens possibilities for assisting the operator through developing computer-based operator support systems (COSSes). At the Halden Project a number of such operator aids have been developed and evaluated through experiments in the experimental control room HAMMLAB with operators from the Halden Reactor or commercial NPPs as test subjects.

These evaluation studies as well as feedback from installations of COSSes in NPPs and other process industries have shown that benefits with respect to both plant safety and economy can be obtained through introducing COSSes in the control rooms.

It is, however, absolutely necessary to perform a careful evaluation and validation of the systems with respect to their usefulness in a control room setting before introducing such operator aids in a NPP control room. This requires utilisation of different methods for man-machine systems evaluation both in the design and implementation phases. A final validation in realistic full-scale simulators with competent operators as test subjects is highly recommended to assure that the introduction of the COSS(es) really facilitates the operators' tasks, without endangering his essential role of maintaining plant safety.

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