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# ENLARGED NORDIC COOPERATIVE PROGRAM ON NUCLEAR SAFETY

## NKA/KRU PROJECT ON OPERATOR TRAINING, CONTROL ROOM DESIGN AND HUMAN RELIABILITY

## SUMMARY REPORT

A Joint Scandinavian Research Project
Sponsored by

The Nordic Council of Ministers

## PROJECT BACKGROUND

The project idea emerged from a contact between the Division of Biotechnology of the Swedish National Defence Research Institute (FOA), and Risø National Laboratory, Denmark in the mid-seventies, before the incident at Three Mile Island caused a general interest in operator problems at nuclear power plants. At FOA, there had been a long tradition for studies of man/system interface problems, and their studies of modern communication systems had led to an interest in models of human information processing. In addition, contacts were established with the nuclear field in Sweden. At Risø, studies of methods for systematic reliability and risk analysis had identified the human operator as a vital element to consider in systems design and analysis, especially during a period when modern information processing technology is being introduced in plant control systems and consoles. This co-operation quickly identified a number of related problems which needed to be attacked simultaneously and the need for a major project with participation by a number of different professional disciplines was evident.

Relevant to all these problems was the impact of computers upon automation of nuclear plants together with the increased awareness of the need to perform systematic risk assessment.

## THE CHANGING TECHNOLOGY

It has for a long time been generally recognised that the advent of a cost-effective, flexible process computer will cause a major change in the role of process operators. Increased levels of automation mean that not only optimization of normal production, but also complex control sequences during plant start-up and shutdown will be automated as well as various important, protective functions. This leads to a change in the role of operators. Instead of being active process controllers, they develop into supervisors and decision makers at a higher level with less direct contact with the plant functions.

At the same time, the problems for system designers change. In the traditional control room, there is typically one indicator for each measuring sensor in the plant. This means that the human factors problems to be solved by the designer traditionally was limited to readability of meters and the right feel of control knobs - the so-called knob and dial ergonomics. In computer-controlled control rooms, the measured data can be preprocessed and combined by electronic data processing. The presentation of information derived from the measured data as well as of information stored from the original design process can be selected and fitted to the operator's immediate task and to his way of coping with the task. Data can be selected, combined and displayed selectively depending on the task the operator is supposed to solve; the format or coding can be chosen depending on the way the operator solves it. This, however, puts system designers in a new situation. To benefit from the potential of the new technology, designers have to know explicitly and in detail what the operators' tasks will be. This was not the case for the traditional technology. Since the data presentation in control rooms consisted of fixed arrangements and operators were introduced to the control rooms as trainees and were trained on the job, there was little need to formulate tasks explicitly except for critical safety-related procedures, and then only in terms of the system's requirements. Thus there was little need to study the mental strategies and information codes used by operators in the tasks.

However, design in the new technology means design based on explicit formulation of task sequences, operator strategies and information requirements in the various work situation contexts.

Furthermore, since large scale installations result in high cost of disturbances of production, "trial and error" training



on the plant is no longer acceptable. In addition, high levels of automation give little opportunity to operators for "hands on" experience and so it is difficult to maintain operator training on the job. This generates an increased need for training methods and facilities outside the plant itself which leads to a formal system for operator education and training incorporating training simulators. This system depends on a formulation of task content and knowledge requirements, expressed in general terms across tasks for the basic education and in task-related terms for simulator training.

Finally, the large consequences/low probability features of nuclear risks lead to a high emphasis on rare events and the importance of effective support of operators in identification and diagnosis of accidental plant conditions. Evaluation of the quality of disturbance analysis systems and support to operators during diagnosis and emergency procedures implies a fundamental problem: how to validate new systems experimentally during rare events? For study of highly skilled operators' responses to complex, unfamiliar rare events, it is difficult to design well specified experiments giving statistically reliable quantitative data, partly because rare events cannot give an abundance of data, and partly because well specified experiments strip the problem of the context. Therefore, it is necessary to develop a new experimental method to evaluate the quality of new designs.

## THE STRUCTURE OF THE PROJECT

This line of reasoning rapidly led to the identification of several topics which would be beneficial to study simultaneously in a single integrated project:

- The actual repertoire of activities and tasks performed by the operating staff of a nuclear power plant and its dependence on the present and future levels of automation.

- The knowledge required for these activities and appropriate means for training plant operators and for competence evaluation and retraining in coping with rare events.

- Models of human operator performance; how do operators read information and make decisions under normal and abnormal plant conditions and how does their performance depend upon control room design?

- The typical limits of human capabilities and mechanisms of human errors as they are represented in existing records of incidents and accidents in industrial plants.

- The general technological trend with respect to automation and information processing, in particular, the potential of process computers for support of operators.

- The use of process computers for improved design of data presentation and operator support systems, especially for disturbance analysis and diagnosis during infrequent plant disturbance.

- Development of experimental techniques to validate research results and proposals for improved man/machine interfaces and other computer-based support systems.

The topics listed are not only important for nuclear power plants, but are vital problems in high risk technology in general as, for instance, the records from accidents in chemical industries during recent years have demonstrated. With this as background, it was found feasible to formulate a major project. It was also found promising to organize it as a joint Nordic project, since existing working groups within Scandinavian research institutes together with their well established contacts appeared to cover the professional ground necessary for carrying out this interdisciplinary project. With assistance from the "Nordic Liasion Committee for Atomic Energy" (NKA) a joint project proposal was made by the following institutes and organizations and covered the topics mentioned:



| | Professional areas of interest: |
|---|---|
| **Sweden:** | |
| National Defense Research Institute, Ergonområd AB | Task analysis, operator training. |
| Studsvik Energiteknik AB | Reactor technology and control, simulators. |
| **Norway:** | |
| Institute for Energy Technology - OECD Halden Reactor Project | Computer and display technology, man-process interface and control system design. |
| **Finland:** | |
| Technical Research Centre of Finland (VTT) | Control and systems engineering, power plant control, training simulators, automation. |
| **Denmark:** | |
| Risø National Laboratory | Operator modelling, human reliability, interface design. |

The original plan appeared in the Nordisk Udredningsserie 1976:28 on Enlarged Nordic Cooperation in Nuclear Safety - appendix 2.5.

## RESEARCH AND RESULTS

In the following section, a brief review of the key research topics of the project is given together with the major results. The activity of the participating working groups has been published concurrently with the research through the normal publishing channels of their national institutes. However, to support overviews of the total effort, technical reports have been prepared for the major areas of the project (refs. 1-4) which give reviews and lists of references for all publications and reports.

The following topics were the basis for the activity during the project:

Systems' Analysis and Description

During a period of changing level of automation and control room design, an important basis for planning of the roles of the operation staff, for design of specific tasks, and for choice of appropriate operator support, is a systematic description of the technical system, its different operating modes, and the control requirements for maintaining as well as for transition between operating modes. In the project, two separate approaches have been taken to this problem.

First, the operating modes of the plant which are generally used in operational planning such as hot and cold shutdown, power production, disturbed operation, etc., have been defined, and the implications in terms of the state of subsystems and equipment have been analysed. Then control requirements and the related operator tasks have been determined partly by technical analysis and review of operating procedures, partly by interviews of the operating staff, as described below. The structuring of the plant information into manageable concepts has been valuable for the understanding of the operators' tasks.

Secondly, an attempt to develop a consistent, formal description of the functional states of the system based on energy and mass flow structures and formal rules for decomposition in subsystems and functions, has succeeded in establishing a formal framework for deriving target states or normal states for subsystems from overall plant goals as well as identifying the related actual states by information integration from measured data. Such an approach gives a basis for detecting



abnormal operation of the plant. The framework also appears to be promising as a tool for synthesizing control programs for sequential control as well as operating procedures and can also be used as a tool for instrumentation planning.

Job Analysis for Operator Training

Based on the description of the plant system in terms of operating modes or states and subsystems/functions, the tasks of the operators related to maintaining states or transfer among states have been studied and formulated from analyses of written work procedures and extensive interviews of the operating staff at Swedish and Finnish power reactors. From a description of the functions of the operators, "typical tasks" have been defined which together form a task repertoire covering the entire field of knowledge and skill required by the staff. Analysis of this set of typical tasks has then resulted in a mapping of the required content of an operator's competence which subsequentially has been used for establishing requirements for operator training and licensing as well as - outside this project - for the design of a formal system for operator qualification and competence evaluation.

Furthermore, the studies of operator tasks and training requirements have been supplemented by an overall study of the conception of operator roles and system goals from interviews of management and plant design groups. This has supported the work with guidelines in identifying the key decisions within the design process.

Analysis of Work Situations

The analysis of typical operator tasks and the requirements for knowledge and skills in general as seen across all tasks is important for planning of operator training and qualification. To serve as a basis for control room design and evaluation, however, they must be supplemented by analysis of typical work situations and associated tasks. Such analyses are necessary to evaluate the workload from simultaneous tasks and to describe the information flow requirements between the plant and the operating staff during typical normal and abnormal situations, and hence the capacity requirements for data displays.

Such analyses have been performed for phases of the plant start-up of Swedish nuclear power plants, and the resulting scenarios have been used for design of information displays as described later. The scenarios have, furthermore, been used for design of experimental situations to validate proposals for new control room designs.

Simulator Training

Simulators are extensively used for nuclear operator training and within the present project a survey of the state of the art of training simulators has been performed. Furthermore, the results of the job and competence analysis have been used to design simulator training courses and evaluate the role of training instructors. In addition, they have formed the basis for "Guidelines for Operator Training Design".

Models of Human Operator Performance

Task analysis and scenarios supply the information about the requirements from the plant for the activity of the operating staff. To plan control rooms based on information technology, however, it is also necessary to have available models of the operator's internal, mental information processes and decision strategies in order to be able to select proper sets of information to be displayed by the computers and to design effective display formats, for instance, in graphic representations.

Such models have until recently only been formulated within avionics for cockpit design, and these models, which are based on control theoretic concepts, have been reviewed. It has been necessary to develop new models which have been derived from analysis of tape recordings of operators thinking aloud, from



interviews and observations in control rooms and from analysis of reports from human errors during plant operation.

The models developed have been very useful for describing typical operator strategies, for instance, for diagnosis, for developing guidelines and criteria for control room design and to formulate the conditions for acceptable human error quantification and prediction. Since the incident at Three Mile Island, the models have met general international interest and will now be evaluated by several independent groups.

Within the project, a first attempt was made to relate these operator performance models based on information processing to the knowledge and skill categories used in operator training.

Operator's Attitudes Towards Automation and Computer-Based Control Rooms

The models of operators' decision making mentioned above take into consideration only the more cognitive functions. The affective factors or emotional attitudes are likewise important, and different methods based on questionnaires and multiple scaling techniques have been developed and tested for evaluation of operators' attitudes to the total situation as well as to the use of different colours for display purposes.

Guidelines and Criteria for Control Room Design

Due to the flexibility of process computers, system designers have great freedom in their choice of the general strategies as well as specific solutions for facilities to support process operators in coping with the complexity of modern plants, and there is a widespread activity in industrial and professional organizations to create relevant design aids and guides. It is also the aim of the present project to present the results of the studies in the framework of design guidelines. Within the project, the general question of guidelines has been approached in two ways. First, a questionnaire dealing with the state of the art and the predicted trends within control room design has been distributed to utilities within the Scandinavian countries and the Halden project signatories and the results concluded for the guidelines. Secondly, a set of design criteria has been proposed on the basis of the operator model mentioned above. A comparison of the consequences of these criteria upon the presently accepted view of "quality of working life" parameters has indicated no immediate conflict, and the general criteria thus established have been proposed and considered internationally in development of design guidelines particularly in the European Workshop on Man/Machine Interface Design (EWICS TC6). The structure of design guidelines proposed from this workshop has in turn been adopted as the frame of reference for the guidelines resulting from the NKA/KRU project.

Proposals for Specific Display Systems

Based on all the previously mentioned projects, an integrated set of displays has been designed for experimental validation in the experimental computer-controlled control room at Halden. The basic aspects which have been emphasized for this system have been the following:

The displays of the set are designed to match the various operator tasks, understood in the way that the target states for systems and functions together with the actual states are represented at the level of the operator's immediate control task. Furthermore, the information presented and the coding chosen are matched to the three possible levels of operator performance, these being skill-, rule- or knowledge-based. Finally, special precautions are taken to support an operator's discrimination between situations when rules and procedures are adequate and must be followed, and situations when this is not the case and the operator must think for himself in order to modify procedures or improvise ad hoc decisions. Several major incidents during the recent years have clearly indicated the latter aspect to be a key problem which must be considered carefully.



In addition to the general structure of a display system, several specific solutions to interface problems have been developed, such as support of operator's recall and use of procedures, automatic diagnostic strategies to guide the operators' use of the individual displays, etc.

These designs have not been experimentally validated within the frame of this project, since the "rare event" problem has led to the need for a consistent experimental technique to be developed.

Experimental System and Methods for Validation

The problems involved in experimental validation of designs for new man/machine interfaces turned out to be more difficult to solve than it was anticipated at the beginning of the project. Two major lines of developments were necessary: The first included the experimental methods to be used as well as the simulator and computer system of the experimental control room. After this, the people participating in the experiments as operators had to be selected and trained very carefully.

The basic methodological problem is related to the fact that new displays or other items of a control room cannot be tested experimentally individually. It is not possible to isolate a display and test its function in the operator's decision making experimentally in a clear-cut, well defined psychological laboratory experiment. This can only be done for specific perceptual coding features such as colours, sizes of symbols, brightness, etc.

Displays play different roles according to the specific situation and must be tested in the complete context including the interference in rare situations of the stereotypes and habits formed during familiar routines. This raises the problem that highly skilled operators cannot be used to test displays different from those related to their skill, since their habits and biases will influence the result in an uncontrollable way. If we to this add the difficulty of getting a reasonable number of results from experimental "rare events", the conclusion is that the traditional way of getting quantitative, hard data to prove the value of a new design must be replaced by experiments aiming at a qualitative understanding of the function of the displays in the context of situations based on real-life scenarios. The method requires special features in the simulator for such scenarios as well as special tools for observation, recording and analysis. These have been established and are being tested.

This has delayed the testing of the specific interface designs mentioned above. However, the experimental facility now established at Halden is expected to be a valuable tool in the development and evaluation of tools for operators' decision making in control rooms.

<u>Human Error Analysis and Quantification</u>

Incident reports involving inappropriate human performance have been analysed in order to test and extend the model of operator performance mentioned previously, and in order to evaluate the possibility of quantifying human error probabilities as a part of a systematic reliability and risk analysis of an industrial process plant. The study was mainly based on analysis of published event reports from U.S. nuclear power plants (Licensee Event Reports, LER) and has been quite fruitful. In addition to supporting the development of the operator model, the human error mechanisms which have been identified have been very useful in the generation of design guides for new control rooms.

Furthermore, the significance of human errors during test and maintenance of safety systems has been substantiated, especially with regard to the role of common mode errors related to the management of task and personnel. Finally, the current methods for human error prediction have been critically reviewed and a set of conditions has been generated, which must be met by the design of operator tasks and systems in order to make prediction feasible. This work has been carried out in



close cooperation with the OECD/CSNI Group of Experts on Human Error Analysis.

ORGANIZATION OF THE PROJECT

It can be seen from the brief review of the topics of the project given above that quite a broad professional area has been covered. Consequently, a considerable number of groups and persons have been involved in the project for shorter or longer periods and the extent of the human resources involved has been considerable.

The coordination of the project has only been possible due to the funds allocated by the Nordic Board of Ministers. This grant made it possible for the steering committee which coordinated the program (see appendix 1) to fund each national group with roughly the equivalent of one qualified researcher. Since this funding was subject to the requirement from the steering committee that at least the same amount of nationally supported effort should also be controlled by the committee, a total of more than eight man-years of effort was each year coordinated by the steering committee. Since this effort in each country related closely to the general national programmes, the informal coordination of the overall activities in Scandinavia as well as their international connections has been considerable. According to the annual NKA/KRU reports, the total extent of the directly coordinated program has been approx. 38 person-years, whereas the indirect national contribution to the project has been of the same order of magnitude.

Important tools for this coordination have been workshops involving all participants (3-4 times a year) as well as periodic exchange of persons amongst the groups - activities which have only been possible due to the funding of the necessary travel expenses by the Nordic Board of Ministers.

PROJECT IMPACT

The NKA/KRU project has had a considerable impact in national as well as international circles.

To begin with, the participating organizations have expressed great satisfaction with the project's approach to the multi-disciplinary character of the problem. They have been particularly gratified by the mutual discussions and cooperation which they feel have enhanced the quality of their own programs and made them more visible in the international scene. Indeed, several of the developed methods, for instance, on task and system analysis, have already been utilized in follow-up studies within Scandinavia as well as outside.

The simulator studies have given rise to the availability of an advanced facility - representative of the coming generation of control rooms - which can make possible "spin-off" studies, for instance, in non-nuclear areas. In addition, there has been created the basis for an experimental approach to evaluating operator performance which has been the subject of considerable international interest. In fact, the same can be said of the concepts of operator behaviour and man-machine interaction which have won international repute in recent years.

The influence of the project with regard to improving the safety of nuclear power should be viewed on a long term basis. The knowledge and practical results which have been obtained within the various contributing organisations is available for dealing with the more practical problems together with representatives from industry.

One industry meeting has already been held in Finland in 1980 which was quite successful in initiating and stimulating interest in problems connected with the ergonomic aspects of plant design and operations. In addition, other contacts with the utilities - for instance in Denmark in the form of a reference group - have been extremely valuable. An international industry meeting in June 1981 is part of the conclusion of the project.



In conclusion, therefore, it is relevant to point out the importance in the coming years of continuing and maintaining these mechanisms for effective cooperation. The means are now available and so are the problems.

REFERENCES

NKA/KRU-(81)12 Technical Summary Report on Operator Training.

NKA/KRU-(81)13 Technical Summary Report on Control Room Design and Human Reliability.

NKA/KRU-(81)14 Publications List.

NKA/KRU-(81)15 Guidelines for Operator Training.

NKA/KRU-(81)16 Guidelines for Man-Machine Interface Design.

APPENDIX 1

Steering Committee for NKA/KRU Project (1980)

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