HPR 312

OECD HALDEN REACTOR PROJECT

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THE EXPERIMENTAL VALIDATION OF THE CRITICAL FUNCTION MONITORING SYSTEM

EXECUTIVE SUMMARY

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EXECUTIVE SUMMARY

by

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March 1984

FOREWORD

The experimental operation of the Halden Boiling Water Reactor and associated research programmes are sponsored through an international agreement by Institutt for Energiteknikk, Norway; The Danish Ministry of Energy; The Finnish Ministry of Trade and Industry; Kernforschungsanlage Jülich GmbH, representing a German group of companies, working in agreement with the German Federal Ministry for Research and Technology; The Italian Comitato Nazionale per l'Energia Nucleare e Alternativa; The Japan Atomic Energy Research Institute; Netherlands Energy Research Foundation; The Swedish Nuclear Power Inspectorate; Central Electricity Generating Board representing a group of Nuclear Research and Industry organizations in the United Kingdom; and from U.S.A.: United States Nuclear Regulatory Commission, and as associated parties: Combustion Engineering, Inc., Electric Power Research Institute, and General Electric Co.

ABSTRACT

The experimental validation of the Critical Function Monitoring System (CFMS) was carried out by the Halden Project in co-operation with the manufacturer, Combustion Engineering Inc. (CE), the Technical Research Centre of Finland (VTT) and Imatran Voima OY (IVO). The CFMS is a computer based system to assist the operating crew of a nuclear power plant to avoid or more quickly identify and respond to abnormal plant conditions. The experiments took place at the PWR training simulator situated at the IVO Loviisa Nuclear Power plant in Finland. The purpose was to assess the impact of the CFMS on operator performance when handling serious plant disturbances. The CFMS project, which lasted more than 18 months, covered all essential details: initial planning, development of a CFMS training programme, specification and installation of data recording equipment, practical training of operating crews, experimentation and data collection, data processing, analysis and evaluation. An effective, modular tape-slide training programme was used for initial instruction. The subjects were twelve crews of experienced operators from the Loviisa nuclear power plant, undergoing their semi-annual retraining at the simulator. The experiments, which employed a 'within group comparison' design, made substantial use of both video and audio recordings, in addition to computer derived measurements. Two transients were developed which presented the operators with two equivalent, severe and complex plant disturbance scenarios. The analysis combined quantitative and qualitative methods, and used a detailed timeline description as the basis for answering questions about the impact of the CFMS. In terms of the overall quantitative analysis, two specific hypotheses were investigated: (1) that operators using the CFMS would maintain critical functions more effectively, and (2) that effective maintenance of critical functions was equivalent to improved plant safety. Both the overall results and the more detailed, qualitative investigation of timeline data supported these hypotheses. In addition, the CFMS project demonstrated successfully the methodology developed at Halden.

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INTRODUCTION

This report provides an executive summary of the experimental validation of the Critical Function Monitoring System. It is intended to provide the reader with a condensed account of the essential features of the project, as well as the main results. For a detailed description of all aspects of the project, including the data analysis and results, the reader is referred to a number of separate reports which are summarized in the list of references.

BACKGROUND

In the nuclear industry it has become widely recognized that information presentation in Nuclear Power Plant control rooms is often inadequate. During adverse plant conditions in particular, the man-machine interface may not provide the necessary support for the operator's decision making. A proposed solution has been to provide the operator with a display of a limited number of critical plant functions derived from a number of plant parameters. The Critical Function Monitoring System (CFMS) is one example of such a system. The critical functions have been selected so that the operator can make a timely and correct determination of the plant state even under adverse conditions.

The fundamental concern of an experimental validation is to assess whether a system performs according to specifications, and to determine whether it provides the expected beneficial effects on operator performance. Very little exists in the way of an established methodology for such a test. The Halden Project undertook to perform an experimental validation of the CFMS, i.e. to assess its impact on operator performance under realistic conditions. It was carried out at the Loviisa Nuclear Power Plant PWR training simulator in Finland, using two complex transient scenarios (cf. Meijer, 1982a).

PARTICIPANTS

The CFMS project was carried out by the OECD Halden Reactor Project in co-operation with the following organizations:

- Combustion Engineering, Inc., Nuclear Power Systems, Instrumentation & Controls Engineering, Windsor, Connecticut, USA (CE)
- Imatran Voima OY, Helsinki & Loviisa, Finland (IVO)
- Technical Research Centre of Finland, Electrical Engineering Laboratory, Espoo, Finland (VTT)

Both CE and VTT are members of the Halden Reactor Project, and the co-operation with IVO was established through VTT. The exchange of technical data concerning the simulator and plant was arranged by VTT. The whole undertaking was co-ordinated by the Man-Machine System group of the Halden Project, using the existing channels of co-operation within this organization. The Halden Project was also responsible for development of the experimental method and for designing the training programme to be used at Loviisa. Assisted by experts from CE, IVO, and VTT, HP carried out the analysis and organized the reporting of the results.

OBJECTIVES

The overall objective of the CFMS project was, of course, to make an experimental validation of the CFMS, i.e., to obtain data which would show the impact of the CFMS on operator performance, hence on operational safety. This was specified in the following objectives:

1. To record and measure reliably operator performance both with and without the use of the CFMS in situations where the safety of the reactor was challenged.

2. To assess the correspondence between the expected and actual effects when the CFMS was used. This relied on an analysis of the data from the experimental sessions, as well as the pre-defined criteria for performance categorisation.

3. To indicate the predictions that can be made about operator performance when the CFMS is used in real-life. To identify the assumptions that underly these predictions and the data on which they are based, and hence express the degree of confidence that can be assigned to them.

4. To assess the problems arising from introducing a new computerised system into an existing control room and operating practice.

The main hypothesis under test in the project was the following:

- During a severe process transient, plant safety with the CFMS will be superior to plant safety without the CFMS.

This was also expressed as two subsidiary hypotheses:

(i) Operators using the CFMS will maintain critical functions more effectively.

(ii) Effective maintenance of critical functions is equivalent to improved plant safety.

According to the design principle of the CFMS, the operator needs the following to accomplish the safety functions: (1) sufficient and intelligible information, (2) comprehensive procedures, and (3) adequate training. The experimental validation of the CFMS tested the first of these three conditons, on the assumption that the two others were fulfilled. It thus became an essential part of the experimental design to ensure that this was so. The experimental design is presented in greater detail in Hollnagel & Marshall (1982).

OBJECTIVES ACHIEVED

This section summarises the extent to which the objectives described previously were achieved.

1. The methodology successfully permitted reliable and accurate recording of operator performance, throughout the experimental runs. It should be noted that operator activity, particularly with respect to CFMS use, could not have been observed accurately without the use of video recording. Generally, the data collection techniques provided a wide data base for subsequent analysis. The results clearly illustrated the complementary role of qualitative and quantitative data in this type of experiment.

   Both of the selected transient scenarios certainly challenged reactor safety; several of the defined critical functions were jeopardised.

2. The data obtained permitted assessment of the way in which the CFMS was used and the effects of this use on a number of measures of plant safety. The way in which this assessment was carried out and the main conclusions are summarised in this report.

   Overall, we concluded that operating crews did use the CFMS to obtain useful information during the test transients and statistical evidence suggested that increased use of the CFMS reduced the threat to critical functions. In terms of operator performance categories the CFMS was most often used for confirmation of alarms; it was only infrequently used in planning and decision for action. In this connection, operators found the concept of success paths difficult to understand. This was largely due to insufficient instruction and/or inconsistencies between CFMS displays and existing panels.

3. Great care must be taken when making general statements on the basis of experimental findings of this type. Nevertheless, given that the subjects were all experienced operators, who took the task very seriously, and that the experimental environment was almost identical to the plant control room, then it was concluded that the content validity was sufficient to allow inferences about the function of the system in a real-life situation, as summarised below:

   - The CFMS fulfilled aspects of the need for an overview of the process during complex transients, particularly by assisting in early process status identification.

   - Loviisa crews operated the plant in a more function-based way than is typical of U.S. operators. This suggests that a CFMS might be more effective in U.S. plants where the functional approach has only been applied recently in rather few stations.

   - The Loviisa control room already included an extensive CRT based information system which was complementary to the CFMS. In control rooms where there is little CRT based information, as is the case in many U.S. plants, it might be expected that operators would be inclined to make more use of a CFMS or similar system.

4. The general view of the Loviisa crews was that the CFMS would be useful at Loviisa. However, they proposed a number of improvements and modifications which are summarised in this report. Most of their recommendations were endorsed by experimental observations. Both emphasised the importance of a proper match between novel displays and the existing representation of the process in terms of instrumentation and control panels.

   When implementing a new information system, there must be a carefully planned training programme for operating staff which should provide a thorough introduction to both theoretical and practical aspects. In this case, greater opportunity for more in-depth instruction would certainly have improved use of the CFMS.

THE CRITICAL FUNCTION MONITORING SYSTEM

The Critical Function Monitoring System must be understood against the background of traditional alarm systems. In such systems the operator is expected to identify the cause for an alarm and correct it if possible. The emphasis is thus on individual faults, rather than on the system as a whole. In contrast to this, the CFMS principle asserts that safe operation of the plant can be accomplished by maintaining a limited number of critical functions. The CFMS contained seven critical functions:

1. Core Reactivity Control
2. RCS Inventory Control
3. RCS Pressure Control
4. Core Heat Removal
5. RCS Heat Removal
6. Containment Isolation
7. Containment Temperature/ Pressure Control

Containment isolation was, however, not implemented in the Loviisa installation. The full details of the CFMS used in the validation are shown in Figure 1, which for each critical function shows its constituent 'legs'.

The CFMS assists the operator in keeping the system under control, by providing him with highly processed information about the status of each of these functions. In addition the CFMS provides detailed information which helps the operator select from the available 'success paths'. A success path is any remedial action which will relieve the threat to an alarmed critical function.

The CFMS installation in the control room consisted of a colour graphic VDU, and a small operator keypad which was used for requesting CFMS displays and acknowledging the CFMS alarms. This was placed adjacent to the central console to facilitate video recording. The CFMS console used in the experimental validation is shown in Figure 2, while the layout of the control room is shown in Figure 3. The CFMS, as installed at the Loviisa simulator, did not contain an audible alarm. The CFMS has been described in greater detail in Meijer (1982b) and Meijer & Rohde (1983).

THE ANALYSIS/TRAINING/ EXPERIMENTATION/ANALYSIS PARADIGM

During the initial planning it soon became clear that an overall structure for the experimental design was necessary. This was specified as the Analysis/Training/Experimentation/Analysis (ATEA) paradigm, and presented and discussed at a workshop meeting on Human Factors Experiments and Validation of Operator Aids in Halden, March 1982.

In the ATEA paradigm the organisation of an experimental validation is divided into four sequential stages. Each stage itself specifies problems and issues that must be considered:

ANALYSIS of system purpose and requirements:

- Specify system purpose and conceptual contents
- Specify man-machine system function
- Specify expected effects and consequences
- Define critical parameters and performance indicators
- Derive 'ideal path' for performance
- Identify constraints (time, money, people, customer's expectations)

CORE REACTIVITY CONTROL Rods not Down Reactivity Increasing Boron Concentration Low	CORE HEAT REMOVAL CONTROL Core Temperature High Loss of Natural Circulation Boiling in Core Boiling in Loops	REACTOR COOLING SYSTEM INVENTORY Pressurizer Level High Pressurizer Level Low Quench Tank Pressure High Quench Tank Level High Quench Tank Temperature High Pressurizer Relief Valve Open Pressurizer Shutdown Level High Emergency Makeup HPSI
REACTOR COOLING SYSTEM PRESSURE CONTROL Pressurizer Pressure Pressurizer Pressure Gradient Cold Stress Temperature Coolant Boiling	PRIMARY CIRCUIT HEAT REMOVAL Steam Generator Level Low Loops Isolated Inadequate ECC	CONTAINMENT TEMPERATURE AND PRESSURE Containment Spray Flow Low Containment Pressure Increasing Containment Pressure Low Containment Temperature High
CONTAINMENT ISOLATION (not implemented)		

Figure 1. CFMS matrix display as implemented at Loviisa

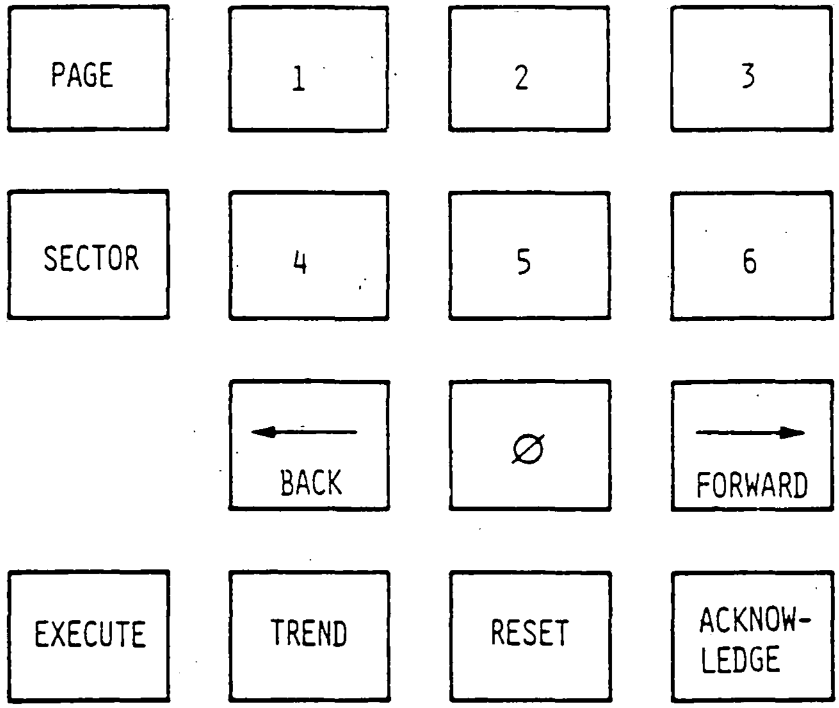


Figure 2. Diagram showing layout of CFMS keypad used at Loviisa

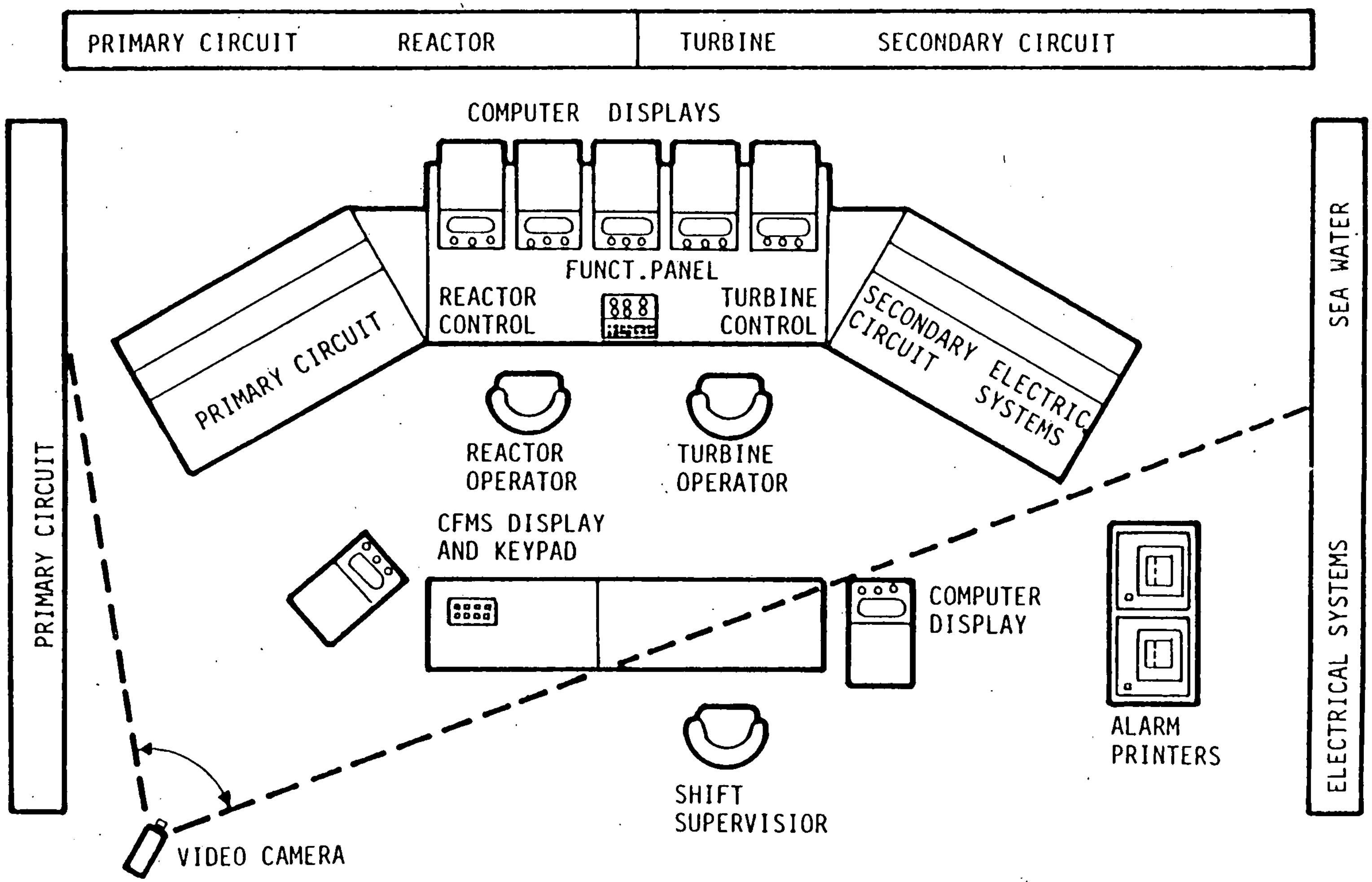


Figure 3. Plan of Loviisa simulator control room showing existing consoles, the CFMS display and position of the video camera used to record operator activity

TRAINING of subjects:

- Derive training requirements from analysis
- Estimate theoretical training and practical training
- Design training programme
- Design training aids
- Implement training programme
- Evaluate training results

EXPERIMENTATION, test of the system under specified conditions:

- Specify experimental design
- Describe experimental conditions
- Define performance measurements
- Record operator performance
- Measure critical parameters
- Record overall system performance

ANALYSIS of performance data:

- Analyse performance registrations
- Describe actual, formal, and prototypical performance
- Analyse and evaluate critical parameters
- Evaluate total system performance
- Interpret results in terms of stated purpose

The ATEA paradigm was successfully used throughout the project to integrate the HP experiment planning. The experience gained will be used to modify and extend the paradigm, so that it can serve as an important tool in future validation studies.

THE EXPERIMENTAL DESIGN

A fundamental concern in validation studies is that the description of crew performance is as reliable and accurate as possible. The basic conditions for a between-groups design are that there are one or more dependent variables from which the effect of the independent variables can be assessed, and that the groups would give a similar performance had the independent variables not been manipulated. None of these conditions can be expected to hold for a realistic validation study, even if the groups are "objectively" presented with the same situation. Therefore, rather than using a between-groups comparison, it was more pertinent to make a detailed analysis of the performance of each crew in a uniform way, with particular emphasis on WHETHER, WHEN, HOW, and WHY the CFMS was used. Accordingly, since a between-groups design was not practicable, the experiment used a within-group design in which each group served as its own control.

In essence, the experimental design attempted to reduce to a minimum the part of the variance of the results which was due to unknown factors. In terms of traditional terminology, the reliability of the data was, in this way, increased. As part of the prior analysis of the experimental conditions, a set of 47 factors were identified which might influence the observed performance. These were divided into six groups as shown below:

1. *THE EXPERIMENTAL ENVIRONMENT*
   E.g., Simulator Fidelity & Equipment Reliability.

2. *THE TRAINING OF THE SUBJECTS*
   E.g., Robustness of Training & Training Schedule

3. *THE TASK*
   E.g., Credibility of Transients & Procedural Support

4. *THE CFMS*
   Intrinsic Characteristics
   E.g., Colour Code, Symbols & System Response Time

   Extrinsic Characteristics
   E.g., Display Compatibility & Appropriateness of Transients

5. *OBSERVATION METHODS*
   E.g, Recording Equipment & Observer Experience

6. *PERSONAL AND SOCIAL CHARACTERISTICS*
   E.g., Motivation & CFMS 'Leaks'

All of the 47 independent factors are discussed in detail in Hollnagel & Marshall (1982). The experiment was designed so that information was available about each factor, thereby allowing its influence to be assessed.

THE TRANSIENTS

In order to suit the CFMS experimental design, two transient scenarios were prepared by staff at VTT. The principal features incorporated in the transient design were as follows:

- They should be difficult
- They should be roughly equivalent in complexity
- The duration should be approximately thirty minutes
- They should present a 'realistic' process situation
- They should challenge several Critical Functions
- They should be unfamiliar to the operators
- They should fit into the retraining programme

The CFMS transient scenarios were developed by VTT in order to comply with these conditions and there was considerable discussion between VTT, IVO and CE before the final versions were agreed upon. Briefly, Transient 1 was essentially a LOCA compounded by problems in the seawater pumps, containment sprinklers and HPSI system. Transient 2 consisted of a complete power blackout together with a failed open pressuriser relief valve. A detailed account of the transients is given in Kautto (1983).

THE TRAINING

In order to make an effective validation of a new operator support system it is essential that the operators are well prepared by means of careful pre-training before any experimental trials take place. A systematic and consistent training programme was constructed for operators taking part in the CFMS experimental validation. The programme consisted of a series of tape-slide modules each followed by exercises designed to check that previously learned material had been understood. The operators gave written answers to the exercises, and any wrong answers were corrected. The training programme contained the following main modules:

1. Introduction to the System
2. The Seven Critical Functions
3. CFMS Display Structure
4. Alarms
5. Access to the CFMS Displays
6. How to use the CFMS

In addition to this class-room instruction, opportunity was provided for structured, hands-on practice with the display system itself. A detailed account of the training programme and instructional material can be found in Marshall et al., (1983).

The results from the training exercises indicated that both introductory and theoretical aspects were learned adequately. However, it was also evident that the operators lacked practical experience in the use of the display during severe process transients. This is not surprising, given that the total time allowed for training was restricted to roughly one working day. With regard to the training technique in general, operators said that although they were not familiar with programmed instruction of this type, they found the training method both interesting and very efficient.

THE SUBJECTS

The entire complement of operators from both units of the Loviisa nuclear power station participated as subjects in the experiments. The subjects were thus all experienced operators who were familiar with working at the simulator. There were twelve crews each consisting of three operators: a shift supervisor, a reactor operator, and a turbine operator. All had at least two years of operating experience, excluding commissioning time. Further background information can be found in Hollnagel et al., (1983).

THE EXPERIMENTAL PROCEDURE

In order to maximise control over the experiment, the following procedure was adopted:

1. Establish a 'Cold' Performance Baseline. The crew was exposed to one of the transients without the use of the CFMS, and without prior instruction about the CFMS. This provided information on how the crew handled a complex transient without the CFMS. The CFMS was, however, in operation outside of the control room during this run to record the status of the critical functions.

2. Training in the use of the CFMS.
   Following the first transient, all crew members were trained in the use of the CFMS by means of the specially designed training programme outlined above.

3. Repetition of the first transient.
   As a final stage in the introduction to the system, each crew again attempted the first transient with the CFMS in operation and available in the control room. This served the dual purpose of a check on the crew's proficiency in using the CFMS, and a check that the introduction of the CFMS did not interfere with their performance.

4. Actual Test Transient.
   On the following day, the crew attempted the second process transient with the CFMS in operation, and available in the control room. This run constituted the principal data source in the experiment.

5. Questionnaires and Interview.
   The actual test transient was followed by a debriefing session. The operators filled out a questionnaire, and were interviewed by a process specialist who had observed their performance.

Each crew thus took part in three experiment trials. To balance out any special effect due to the sequence of the transients, six crews experienced transient 1 before transient 2, and six attempted transient 2 before transient 1. The order of the two transients selected for the experiments was distributed randomly among the twelve crews. The experiments took place at Loviisa from September through December 1982. The experimental procedure is presented in detail in Heimburger & Sammatti (1983) and Hollnagel & Marshall (1982).

DATA TYPES

In accordance with the experimental design, three major categories of performance data were recorded:

Category 1: Directly Recorded Real-Time Data

- Video recording of operator activities, which provided an account of operator movements.
- Audio recording of verbal communication within crew, and between crew and instructor.
- Computer registration of plant alarms and control room operations.
- CFMS logs of display requests and a time history of analogue and binary parameters transmitted to the CFMS from the simulator, as well as parameters computed by the CFMS itself.

Category 2: Derived Real-Time Data

- Critical function leg alarms.
- Plot files for analogue variables.
- Critical control room operations and filtered plant alarms.
- Merged time lines.

Category 3: Non Real-Time Data

- Training scores.
- Observer's action check list.
- Questionnaires.
- Post-experimental interviews.

Altogether these data types covered all essential aspects of operator performance, and constituted a sufficient basis for subsequent analysis. They are described in greater detail in Hollnagel (1983). The processing and handling of the data was accomplished by means of a system of computer programs developed for the purpose.

DATA ANALYSIS STAGE 1 - CO-ORDINATION OF DATA TYPES

All data obtained during the testing sessions were transmitted to the Halden Project for use in evaluating the results of the experiments. All data types were subjected to a processing procedure which converted the real time data to a common data format for ease of use during later analysis. This standardization procedure also provided for the translation of all Finnish text to English, as well as converting the times in all data records to elapsed time from the start of the experimental run.

The processed data files were then further refined through the application of filtering and selection programs which chose those subsets of the data which were most appropriate for the evaluation of CFMS use, operator performance, and plant safety status based on specific aspects of the experimental transients. Summary statistics were extracted for use in later stages of the analysis, and important plant parameters were plotted along the same time scale for each run. Detailed timeline files were created for each experimental session by combining several data subsets, namely operator comments and movements, significant plant alarms and control room operations, CFMS display requests, and critical function algorithm alarms from the CFMS itself. Details of the data handling processes are given in Hunt et al., (1983).

ANALYSIS STAGE 2 - OVERALL CREW PERFORMANCE

An important aspect of the CFMS experiment was to investigate and evaluate ways of obtaining quantitative measures of operator activities pertaining to use of the CFMS. Three major factor categories were derived from the experimental data: CFMS use by operators, CFMS status during experimental trials and plant performance parameters. Statistical techniques were applied to determine the relationship between these performance factors.

One description of the overall crew performance was based on a quantitative analysis of measured operator and plant performance factors. This approach to the analysis required the combination of a large amount of data from a variety of sources thereby providing a comprehensive overview of CFMS use. The CFMS use could, however, not have been measured in any detail without the use of the video camera in the control room. The visual record provided data about which of the operators was using the display and the recorded verbal exchanges between crew members revealed a great deal of information about how they employed the CFMS in their response to the transient.

Clearly the operating crews did use the CFMS to obtain useful information during the test transient. The supervisors used the display the most and derived most benefit from it. Overview displays were used to the greatest extent, the primary circuit overview receiving the most attention, followed by the CF Monitor and the core overview respectively. The main use of the CFMS was on the primary side, i.e. reactor operator plus shift supervisor. This was mostly due to the nature of the transients.

Quantitative statistical analysis strongly suggested a negative relationship between various factors which measured the number of CF alarms and factors reflecting usage of the displays. This finding was in accord with the original hypothesis, but more detailed analysis of individual CFMS use would be required to establish any causal link between these measures. The correlational analysis also confirmed the supervisor as a predominant factor in use of the system.

The amount of heat in the primary system seemed to be the overriding CF factor which was sensitive to use of the CFMS for these transients. However, there was no straightforward relationship between the plant performance parameters and the CF status factors. A more detailed engineering analysis indicated that the somewhat paradoxical findings observed were due to confounding effects between some of the performance factors (Nelson, 1983). The extended analysis indicated that the Core Boiling performance parameter was the best indicator of plant safety. It correlated highly with CF status.

Overall crew performance was also described as it appeared from the key activities and observer's checklists. The key activities checklist was defined by VTT, based on a description of the transients. The checklist was scored from the timeline description produced by HP. For each key activity it was noted whether the crew had carried it out, when it occurred, and, if possible, what the delay was from the appropriate signal or alarm. For the actual test transient, the use of the CFMS in relation to these activities was also noted.

The results revealed neither consistent nor obvious differences between crews in the sense that any one crew was significantly better or worse than another. Some activities were generally missed by the crews, independent of the use of the CFMS. Moreover, the analysis of key activities clearly showed a substantial variation in how crews performed the task, with respect to number of key actions as well as their sequence. Recorded delays from alarm onset to action were too few to permit a general analysis, although one case showed significant improvement with CFMS use. As noted above, there were no audible alarm signals available from the CFMS.

This variation was also true for the number of key activities carried out, as well as their order.

No two crews carried out the same key activities in the same sequence, even though the experimental conditions were as similar as possible. These findings supported the choice of a within-group rather than a between-group experimental design.

Analysis of the questionnaires showed that learning the CFMS was quite easy, both in terms of the underlying principles of the display and practical application. The primary display features were all easy to understand. Although consistency between CFMS and Loviisa information presentation was judged by some crews to be low, specific effects of this could not be detected from the questionnaires or from the analysis of the performance; operators, however, mentioned it in the post-experimental interviews. Opinions differed among the operators about the usefulness of the CFMS, more general applications being rated higher than specific ones. The experimental task (i.e., coping with the transient scenarios) was considered difficult by all operators.

ANALYSIS STAGE 3 - CFMS USE BY INDIVIDUAL CREWS

The third stage in the analysis was to characterize in detail the performance of individual crews. The basis for this stage of the analysis was the key activities checklist, appropriate parts of the timeline, and a summary of CFMS utilization.

The use of the CFMS in connection with the key activities was analysed for each crew. CFMS use was described in terms of a basic model of decision making, i.e., detection, decision, and control. Analysis in these terms was, however, restricted because it would have involved extensive extrapolation of data from the video and audio recordings. In addition such a study would have demanded the close co-operation of a Finnish speaking process expert over a considerable time period.

Even though the analysis was made from a subset of the complete performance description, it nevertheless provided detailed support for the conclusions reached in the second stage. The displays that provided a general overview of plant status were most often used, and in many cases the CFMS provided operators with timely information relevant to the handling of the transient.

In this way the third stage of analysis, based on individual crew data, provided support for the conclusions from the overall performance analysis. It showed when the operators used the CFMS, how they used it, and what the outcome of use was. The display was most often used in connection with detection or confirmation of alarms. It was only infrequently used in planning and decision for action, perhaps because operators found it difficult to understand the concept of success paths. The display pictures most often used were the primary overview and the CFMS monitor, i.e., those pictures which, in particular, provided an appropriate overview of the plant status. The detailed analysis suggests that the CFMS served the operators well and, in a number of observed instances, it did provide useful information.

THE POST EXPERIMENTAL INTERVIEWS

Observation and interviewing of each crew was carried out by IVO staff during and after the final experimental run (Rinttila & Makkonen, 1983). In addition to questions relating directly to the CFMS, there were questions referring to the transients and about the use of other control room facilities.

The observation during the transients was based on pre-planned lists of anticipated events, decisions and operations, which were discussed after the transient between the crew, the simulator instructor and the observer.

Naturally there was considerable variation in answers received during the interviews as there was in the use of the CFMS. The main points concerning the use of the CFMS are summarized below:

AVAILABLE TIME.

All crews agreed that familiarization time with the CFMS was too short.

CRITICAL FUNCTIONS.

Crews had certainly accepted the idea of critical functions and regarded those, implemented at Loviisa, as reasonable and sufficient for safety supervision. They found them easy to remember, and agreed that it was crucial to control these functions whenever plant safety was at risk.

VALUE OF THE CFMS.

Six out of the 12 crews felt that the CFMS did not influence their actions during the experimental transients, whereas the remaining six definitely considered that they had derived some benefits from the system. Nevertheless, each crew remembered some useful piece of information received via the CFMS. In addition, all operators felt that the CFMS should and could have been utilized more effectively.

PROCESS DIAGNOSIS.

Those crews who found the CFMS valuable, said that it helped particularly in diagnosing plant status. Diagnosis was performed faster and more reliably, because the CFMS directed their attention to the most essential safety functions. The CFMS was often used for confirming diagnoses.

SYSTEMATIC TRANSIENT MANAGEMENT.

As a more subjective judgement, the observer noticed that, in many runs, plant operation was more purposeful and systematic than on earlier occasions even though the CFMS transients were more complex and difficult than previous simulator exercises.

USE OF DISPLAYS.

The interviews confirmed that crews restricted CFMS use to first and second level displays. The main reason for this was that the third level displays were largely the same as those already available from the plant computer. Therefore these CFMS displays did not contain any new information. Further, diagram conventions used in the CFMS pictures did present some inconsistencies with the existing process mimics. This understandable reluctance to use the lower level display was aggravated because there was only one CFMS display unit available and thus overviews and detailed pictures could not be inspected simultaneously.

SUCCESS PATHS.

Although success paths are an essential part of the CFMS concept the Loviisa operators did not apply them effectively. A number of reasons were suggested for this:

- The link between the critical functions and corresponding success paths was not clear enough.
- The success paths were shown on third level pictures which were not often used by the operators.
- The idea of success paths was not handled sufficiently during training.

The general view of the Loviisa crew was that a critical function system similar to the CFMS would be useful at Loviisa. However, they would not be very happy with the implemented system as such, but proposed some improvements and modifications. These are summarized below.

- One display unit was not sufficient. There should be two or three CFMS display units. One unit could be dedicated to displaying the first level overview.
- The reactor operator display units should be at the operator's desk.
- The display hierarchy should be linked more clearly with the critical functions.
- The critical function system should be integrated better with the existing control room systems. Any unnecessary overlapping should be avoided.
- The quality of the displays could be improved in terms of colour and definition.
- A common proposal was that the CFMS should be restricted to overview displays only. On the other hand, suggestions were also made for extending the application of the CFMS concept to non-safety functions. In this case the turbine operator would also benefit from the system.

When evaluating operator opinions of the CFMS, it should be remembered that these opinions were related to the system as it was implemented at Loviisa. These views, therefore, should not be generalized without careful consideration. However, the findings, demonstrated clearly the importance of careful integration when installing a novel system in an existing control room.

POST EXPERIMENTAL FEEDBACK SESSIONS

Feedback sessions were held with the operators after the completion of the first stage of data analysis. All operating crews were invited to these meetings where VTT, IVO and HP staff discussed general aspects of the project. The overall impression gained was that the operators enjoyed taking part in the experiment. They were interested in both the concept of critical functions and the CFMS display. They agreed that the transients themselves were certainly challenging. With regard to video recording in the simulator control room, although operators had expressed some initial unease, they had not found the recording apparatus at all intrusive during the experimental runs.

DISCUSSION OF METHOD

Since a behavioral study on this scale is difficult to repeat, and almost impossible to replicate, experimental planning is extremely important. In this case planning for the experiment was certainly adequate and indeed contributed significantly to the success of the project. It should, however, be emphasized that constraints must be made explicit as early as possible, both with regard to resources and the delegation of tasks and responsibilities.

Although none of the main points were missed, the planning of the data collection and analysis was not completely successful. The main problem was that preliminary planning did not go into sufficient detail with regard to data processing and analysis. It might have been advantageous to reduce the amount of total data collected, but this was very difficult to specify beforehand.

Overall the experimental method was found to be adequate for the purpose. Considerable variation in crew performance was clearly demonstrated, even under highly similar experimental conditions. Consequently we would recommend that a between-groups design should only be used when the task is considerably less complex that this one. Furthermore, the analysis of the CFMS data provided a good illustration of the complementary role of qualitative and quantitative types of data analysis.

A basic question in the CFMS project was the content validity of the test situation. The operating crews were all experienced operators, and the experimental environment was almost identical to the real plant control room. The analysis of the timelines showed that the operators took the situation very seriously, even though they considered that the experimental transients, while plausible, would be very unlikely to occur in reality. The CFMS test installation was representative in terms of functional completeness, except that the operators lacked extensive practical experience with the system. In spite of this reservation we have concluded that in general the content validity of the test was sufficient to allow inferences about the function of the system in a real-life situation.

SUMMARY OF CONCLUSIONS

For convenience this summary has been divided into two sections: Firstly, conclusions derived from the experiment about the CFMS itself, and secondly, conclusions about the experimental methodology.

The CFMS

The main conclusions are listed in the following table. These conclusions are based on analysis of three different broad segments of the experimental data base:

1) Overall quantitative assessment of CFMS use.
2) Detailed analysis, both qualitative and quantitative, of the individual summarized timelines.
3) Analysis of questionnaires and post-experimental interviews.

Analysis concentrated on the third experimental run when all crews were familiar with the experimental setting and were most experienced with the CFMS. Because of the small sample size, conclusions based on one data category have, where possible, been supported by seeking confirmation in the other two major categories. In the table, '1' indicates a primary source for the conclusions, while '2' shows sources which provided confirmation. The results thus illustrate how different types of analysis (qualitative and quantitative) can require and support each other.

In general it is concluded that operators did use the CFMS to obtain valuable information which assisted in their handling of the serious plant scenarios. Given the high degree of content validity in the experimental situation, and the wide range of the data base, it is considered reasonable to expect that these findings will generalize to the real plant environment. Moreover, it is inferred that certain aspects of the experimental conditions tended to lessen the possible beneficial impact of the CFMS on operator performance:

Firstly, the Loviisa control room already included an extensive CRT-based information system. Therefore it was to be expected that during an unknown serious transient, operators would be inclined to resort to their own, more familiar, information system than to the less familiar CFMS. This would explain those occasions where the CFMS was used for confirmation after the transient had been brought under control. It could be suggested that in control rooms where there is little or no CRT-based information, as is the case in many U.S. plants, operators would be more inclined to utilize a CFMS or similar device.

Secondly, it became clear during the project that the Loviisa crews operated the plant in a more function-based way than U.S. operators. In other words, Loviisa operators' responses to a serious transient tended to be both less event based and less procedure oriented than would be the case in the U.S. This would again suggest that a CFMS might be more effective in the U.S. where the functional approach has only been applied recently and in relatively few plants.

Finally, it was clear that the CFMS fulfils to a considerable degree the need for a process overview to assist in the early identification of plant status during a transient. However, the experiment revealed the importance of compatibility between the mode of information representation used in new displays and existing instrumentation.

The Methodology

The planning of the experiment showed the importance of making constraints explicit as early as possible, with regard to resources and delegation of tasks and responsibilities. Advance planning of data recording, processing, and analysis was not sufficiently detailed, but these matters are difficult to specify a priori. The experimental method was adequate. CFMS use could not have been measured in any detail without the use of video and audio recordings. Despite some initial unease, the recording apparatus was not found to be intrusive.

The analysis of key activities clearly showed substantial variation in crews' performance in terms of the number of key activities and their order, despite highly similar experimental conditions. Scoring of crew performance was consistent between crews.

Training results indicated that introductory and theoretical aspects were learned adequately. The idea of success paths was not treated sufficiently during training. Operators also lacked extensive practical experience with the use of the display during severe process transients. Questionnaire analysis showed that learning the CFMS was quite easy, both for principles and practices. Operators found the training method both interesting and efficient.

Crew members were all experienced operators and the experimental environment was almost identical to the plant control room. The operators took the situation very seriously. Consistency between CFMS and Loviisa information presentation details was low, but specific effects were not detected. It was concluded that the content validity of the experiment was sufficient to allow inferences about the function of the system in a real-life situation.

The methodology developed by HP was clearly adequate and as such presented an advance in the available, proven techniques for the validation of man-machine interfaces. From the outset the objective of the project was to evaluate the CFMS during unknown serious nuclear plant events in an existing, realistic control room environment. We feel that this was accomplished with some significant success.

ABBREVIATIONS

ATEA	- Analysis/Training/Experimentation/ Analysis
CE	- Combustion Engineering
CF	- Critical Function
CFMS	- Critical Function Monitoring System
ECCS	- Emergency Core Cooling System
HP	- Halden Project
HPSI	- High Pressure Safety Injection
IVO	- Imatran Voima OY
LOCA	- Loss of Coolant Accident
OECD	- Organization for Economic Co-operation and Development
PWR	- Pressurized Water Reactor
RCS	- Reactor Coolant System
VDU	- Visual Display Unit
VTT	- Valtion Teknillinen Tutkimuskeskus (Technical Research Centre of Finland)

REFERENCES

The following pages list the documents that have been published as a part of the CFMS project. For each document a brief characterization of its contents is given. Note that the accessibility of some documents may be restricted. Further information can be obtained by writing to the organization where a document was originally issued, normally the organization of the first author.

Heimburger, H. & Sammatti, P. (1983). Experiences of the practical arrrangements at the Loviisa training simulator (LOKS) during the CFMS project. Helsinki, Finland: Technical Research Centre of Finland and Imatran Voima OY. (Paper presented at the Enlarged Halden Programme Group Meeting, Loen, Norway, 24th - 27th May, 1983.)

The paper describes briefly the experiences gained from the preparation of the test site and the practical execution of the experiments. The time table of one experiment and the task distribution among the research staff is included. Some improvements to the LOKS itself and to the experimental arrangements are discussed. Based on the experiences from the Loviisa training simulator a conclusion is that it was useful to combine the training and the research aspects.

Hollnagel, E. (1983). Description of data types in the validation of the critical function monitoring system. Halden, Norway: OECD Halden Reactor Project HWR-61.

This report was written as part of the preparation for the CFMS project. It gives a description of the various types of data that could be recorded in the experiment and relates them to the purpose of the CFMS project. It also discusses the nature of man-machine systems experiments, in contrast to 'engineering' experiments and 'human factors' experiments.

Hollnagel, E., Hunt, G.L. & Marshall, E. (1983). The experimental validation of the critical function monitoring system. Preliminary analysis of results. Halden, Norway, OECD Halden Reactor Project HWR-111. (Paper presented at the Enlarged Halden Programme Group Meeting, Loen, Norway, 24th - 27th May, 1983).

The report presents a detailed description of the CFMS experiments, starting with the background for the CFMS project. It contains a thorough discussion of the three stages of the data analysis, including the statistical analysis, the analysis of the questionnaires, and the analysis of the individual crew performance. The data and results needed to support these analyses are included in the report.

Hollnagel, E. & Marshall, E. (1982). The methodology of the CFMS project. Halden, Norway: OECD Halden Reactor Project HWR-77.

This report was written as part of the preparations for the CFMS project. It presents the method in detail, and relates it to earlier studies of a similar nature. It identifies the factors that can influence the outcome of the experiment, and discusses them one by one, with emphasis on the way in which their influence can be assessed and possibly controlled.

Hunt, G.L., Marshall, E. & Hollnagel, E. (1983). Data management in large-scale simulator experiments. Halden, Norway: OECD Halden Reactor Project HPR-302. (Paper presented at the Enlarged Halden Programme Group Meeting, Loen, Norway, 24th - 27th May, 1983).

Three categories of experiment data (simulator state information, CFMS state information, and audio/video recordings of control room activity) were identified along with the methods and hardware needed to acquire them during all test transients at Loviisa. The resulting data sets were transferred to Halden Project computers, translated from Finnish to English, converted to a standardized data record format, and synchronized (in time) for each of 36 transient runs. Subsets of the data were formed into a detailed timeline record of each transient for later detailed review by analysts. Other subsets were processed to derive statistical, analytical and graphical representations of CFMS use and operator/plant performance.

Kautto, A. (1983). The transients of the critical function monitoring system (CFSM) validation test. Helsinki, Finland: Technical Research Centre of Finland. (Paper presented at the Enlarged Halden Programme Group Meeting, Loen, Norway, 24th - 27th May, 1983).

This paper, written from the point of view of safety, gives an account of the Loviisa process (Pressurized Water Reactor) in order to make it easy for the reader to understand the transients developed for the CFMS validation experiments. The reliable way to test a system for supporting the operator's decision making is to use a full-scope simulator, because that makes it possible to generate 'new' accident sequences by the interaction of simultaneous malfunctions, changing the order of malfunctions, and varying the severity of the malfunctions. The CFMS test transients took advantage of these features, which are fully described in this paper.

Kautto, A., Marshall, E.C., Rohde, K. & Makkonen, L. (1983). The experimental validation of the critical function monitoring system. (Paper presented at the IAEA&NPPCI Specialist's Meeting on Nuclear Power Plant Training Simulators, Otaniemi, Finland, 12th - 14th September, 1983.)

This paper provides a description of the Loviisa process and how the CFMS was implemented in the simulator control room. It also contains a fairly detailed outline of the transient scenarios used in the experiments.

Marshall, E., Hollnagel, E. & Tuominen, L. (1983). The experimental validation of the critical function monitoring system. The training programme. Halden, Norway: OECD Halden Reactor Project HPR-303. (Paper presented at the Enlarged Halden Programme Group Meeting, Loen, Norway, 24th - 27th May, 1983.)

In order to make an effective validation of a new operating system it is essential that operators are well prepared by means of careful pre-training. A systematic and consistent training programme was constructed for operators taking part in the trials. It consisted of a series of tape-slide modules, written exercises and opportunity for structured, hands-on practice with the display itself. Results from the programme indicated that introductory and theoretical aspects were learned adequately. This conclusion was borne out by responses to the questionnaire filled out by all subjects after the experiment. However, it is evident that, due to the restricted time available, trainees lacked practical experience in use of the display. Nevertheless, operators found the programmed approach to training both interesting and efficient.

Marshall, E., Makkonen, L., Kautto, A. & Rohdé, K. (1983). An account of the methodology employed in the experimental validation of the critical function monitoring system. (Paper presented at the IAEA/NPPCI Specialist's Meeting on Nuclear Power Plant Training Simulators, Otaniemi, Finland, 12th - 14th September, 1983).

An experiment on this scale generates a great deal of valuable data. In this case, it took the form of video-tape recordings of operator activity, computer logs of plant parameters and control actions, as well as observational records. In addition, questionnaires and interviews were administered by instructors after the experimental sessions. This paper describes methodological aspects of the overall analysis and shows how these diverse data sources were combined to produce a coherent overview for assessment of the impact of the CFMS on plant operation.

Meijer, C.H. (1982a). On the validation of operator aids for nuclear power plants. (Paper presented at the Halden Project Workshop on Human Factors Experiments and Validation of Operator Aids, Halden, Norway, 9th - 10th March 1982).

This paper addresses some of the more general aspects of the validation of operator aids for nuclear power plants. The validation is discussed in terms of the generic requirements for operator aids and the steps needed to verify that these requirements have been fulfilled. The early concepts of the Critical Function Monitoring System (CFMS) programme, as jointly performed between Combustion Engineering, Inc., the OECD Halden Reactor Project, and the Technical Research Centre of Finland, are highlighted. This programme included the validation of the CFMS at the Imatran Voima OY owned and operated Loviisa PWR training simulator facility at Loviisa, Finland.

Meijer, C.H. (1982b). Computer-based operator support systems. Windsor, Connecticut: Combustion Engineering, Inc., IPD82-53. (Paper presented at the Third Coorporate Technological Awareness Conference, Atlanta, Georgia, 29th - 31st March, 1982).

This paper addresses the Combustion Engineering, Inc., approach to meet some of the later needs for improvements to the man-machine interfaces that aid the operator to monitor, control, and diagnose the plant during normal and abnormal operation. The principles of an early version of a Critical Function Monitoring System (CFMS), as an aid to the plant operator to monitor and control a finite set of critical plant safety functions, are discussed in detail. The ap-

proach is based upon C-E's many years of experience in designing and licensing PWR's and developing its NUPLEX 80-TM advanced control center for this type of plant.

Meijer, C.H. & Rohde, K. (1983). The CFMS: An aid to improve man-machine interaction. Windsor, Connecticut: Combustion Engineering, Inc. (Paper presented at the Enlarged Halden Programme Group Meeting, Loen, Norway, 24th - 27th May, 1983).

It has been widely recognized that the existing man-machine interfaces in nuclear power plant control rooms are not adequate to effectively aid the operator in diagnostic or decision making activities. The critical function monitoring system (CFMS), developed by Combustion Engineering, addresses this problem by providing the operator with an integrated display of a minimum number of plant parameters, designed to provide a timely and accurate determination of the safety status of the plant. A unique feature of the CFMS is the implementation of sophisticated algorithms, oriented at plant dynamics, which represent the operator's basic cognitive process as related to the determination of critical function status. The CFMS has been installed in operating plants in the USA, and preliminary evidence indicates that it has been well accepted by the operating crews as an effective operator aid.

Nelson, P.R. (1983). Loviisa CFMS algorithm - performance factor correlation analysis. Windsor, Connecticut: Combustion Engineering, Inc., Internal Note F46222.

This report contains the results of an analysis of the correlation matrices of CFMS algorithms versus plant performance factors, made in terms of plant safety. The findings indicate that core boiling was the dominant performance factor. This factor exhibits a positive correlation with the majority of CFMS algorithms. It is suggested to upgrade available data on overall performance in order to derive alternate performance factors or enhance those already utilised.

Rinttila, E. & Makkonen, L. (1983). The experimental validation of the critical function monitoring system. Results from post-experimental interviews in CFMS validation. Helsinki, Finland: Imatran Voima OY. (Paper presented at the Enlarged Halden Programme Group Meeting, Loen, Norway, 24th - 27th May, 1983).

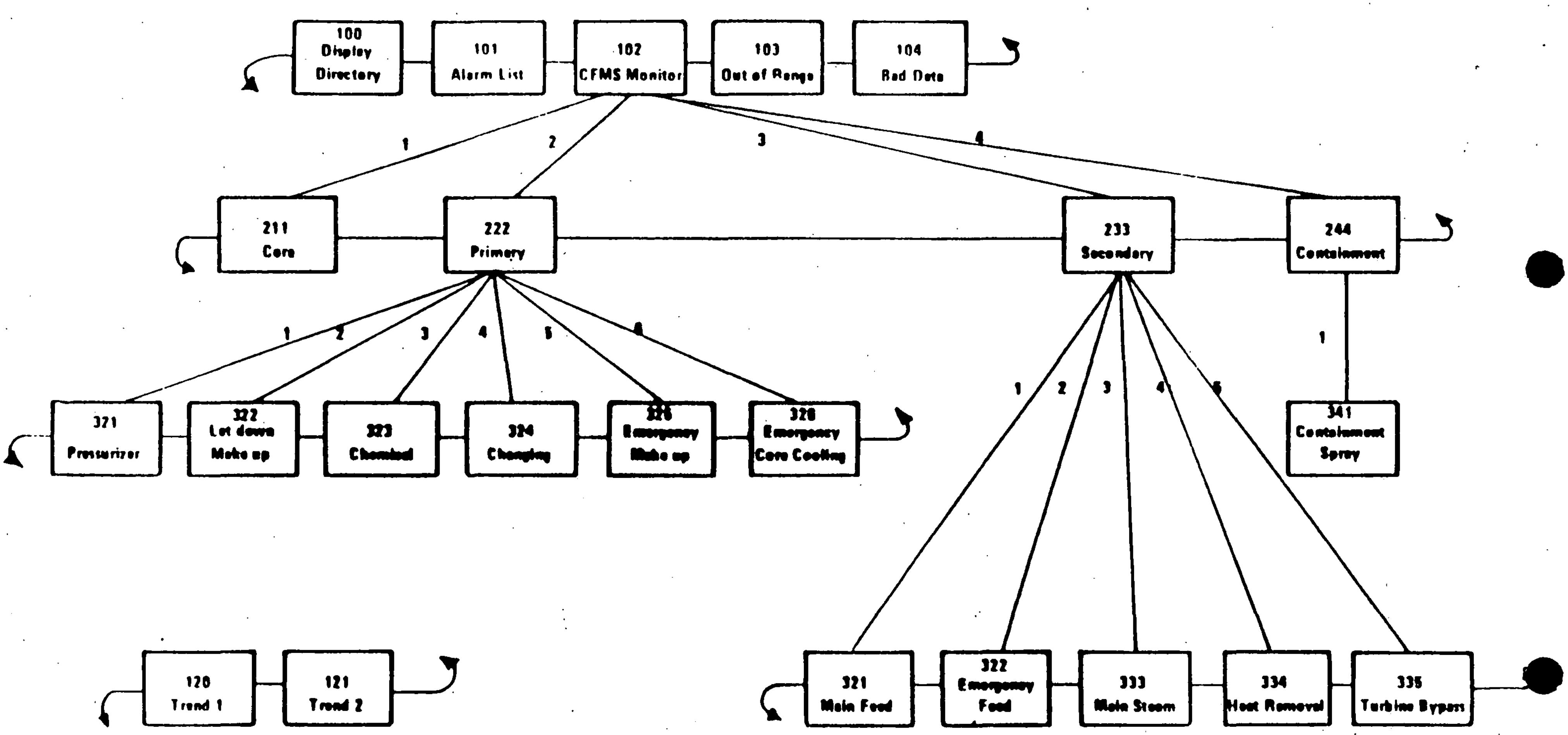
Each crew was interviewed after the final experimental run by an IVO appointed specialist who had also observed the experiments. The interviews were based on a prepared list of questions. One conclusion from the interviews and observations was that the idea of critical functions was accepted by the Loviisa crews. Because of insufficient time for familiarization and certain deficiencies in the CFMS implemented at Loviisa, the operators could, however, not make as much use of the CFMS as they would have liked to. A system such as the CFMS would nevertheless be useful in the Loviisa control room if some improvements were made to the displays and if the system was better integrated with the existing control room.

Wahlström, B., Smidt-Olsen, H., Rinttila, E. & Meijer, C.H. (1983). Experimental validation of an operator support system using a training simulator. (Paper presented at the IAEA International Symposium on Operational Safety of Nuclear Power Plants, Marseilles, France, 2nd - 6th May, 1983.)

It has been widely recognized in the nuclear industry that the man-machine interfaces in nuclear power plant control rooms might not adequately support the operators' decision making during adverse plant conditions. One proposed solution has been to provide the operators with an aid by displaying a small number of critical plant parameters selected to achieve a timely and correct determination of the plant state during these conditions. Very little evidence, however, exists on the benefits of such operator aids and how they should be used in an actual control room environment. The paper describes a project to experimentally validate a so-called Critical Function Monitoring System in terms of its usefulness to the operators in handling two complex adverse transients run on a full-scope training simulator.

SUMMARIZED CONCLUSIONS BASED ON EXPERIMENTAL RESULTS

	Overall Assessment	*Detailed Analysis*	*Questionnaire & Interview*
Increased CFMS display use reduced number of CF alarms.	1	2	-
CFMS was most often used for detection or confirmation of alarms; only infrequently used in planning and decision for action.	2	1	2
It was difficult to understand link between success paths and CF.	-	2	1
The success paths were shown on third level pictures which were infrequently used by the operators.	1	2	2
General uses of the CFMS rated higher than specific uses. In particular, the overview display (primary and CF monitor) were used the most.	1	2	2
The test task was considered difficult by all operators.	-	2	1
Crews did use the CFMS to obtain useful information during test transients.	2	1	2
Amount of heat in primary system was the CF factor most affected by CFMS use. Core boiling was dominant plant performance factor.	1	2	-
Supervisor was the predominant user of the CFMS.	2	1	-
CFMS should be better integrated with the existing control room systems.	-	-	1
There should be several dedicated CFMS display units.	-	2	1



CFMS Display Hierarchy Implemented at Loviisa

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PRIM.PIIRIN MASSATASE

YP10L002 MATALA PUHALLUSSLO TAYTTYY VAROVENTTIILI AUKI	1
MATALISAVESI TJ	5
ULOSLASK/LISAVESI	2
NORMAALILISAVESI TK	4

PRIM.PIIRIN PAINE

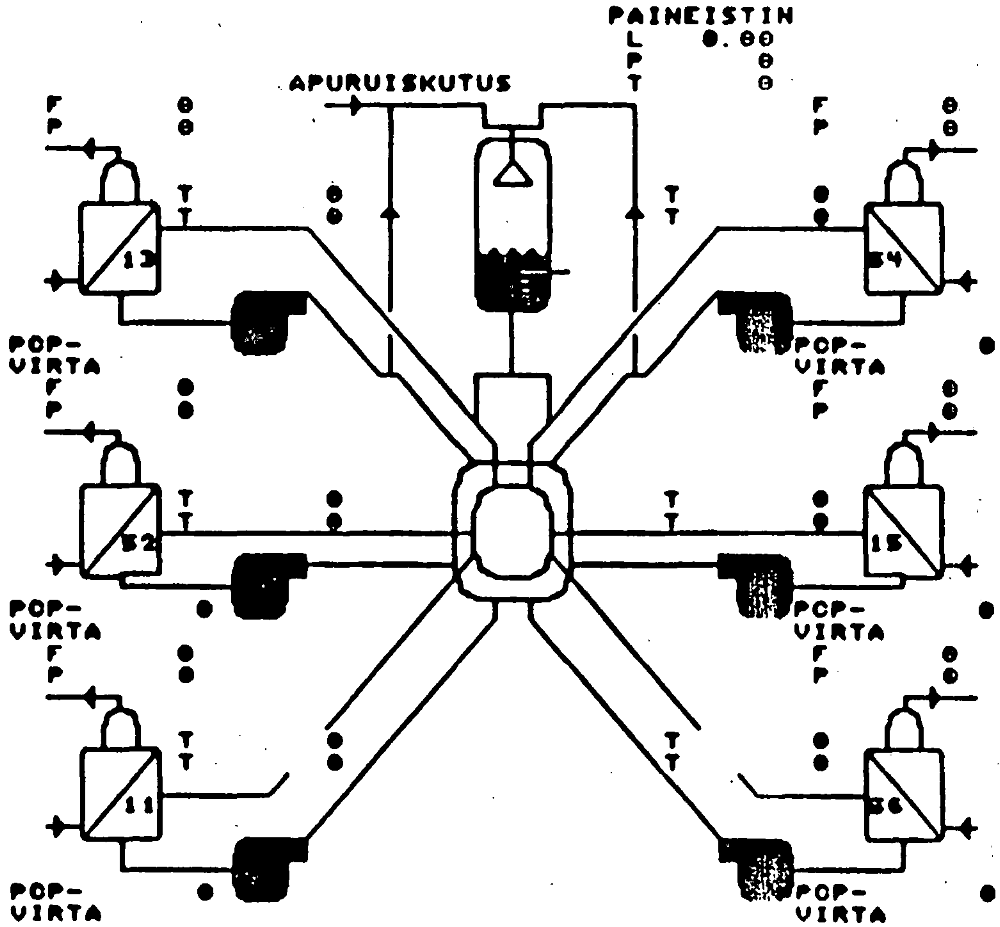
YP10P001 SUURI JAAHDYTE KIEHUU YP10P001 SUURI GRAD. KYLMAHAURAUSLAMPOT.	1

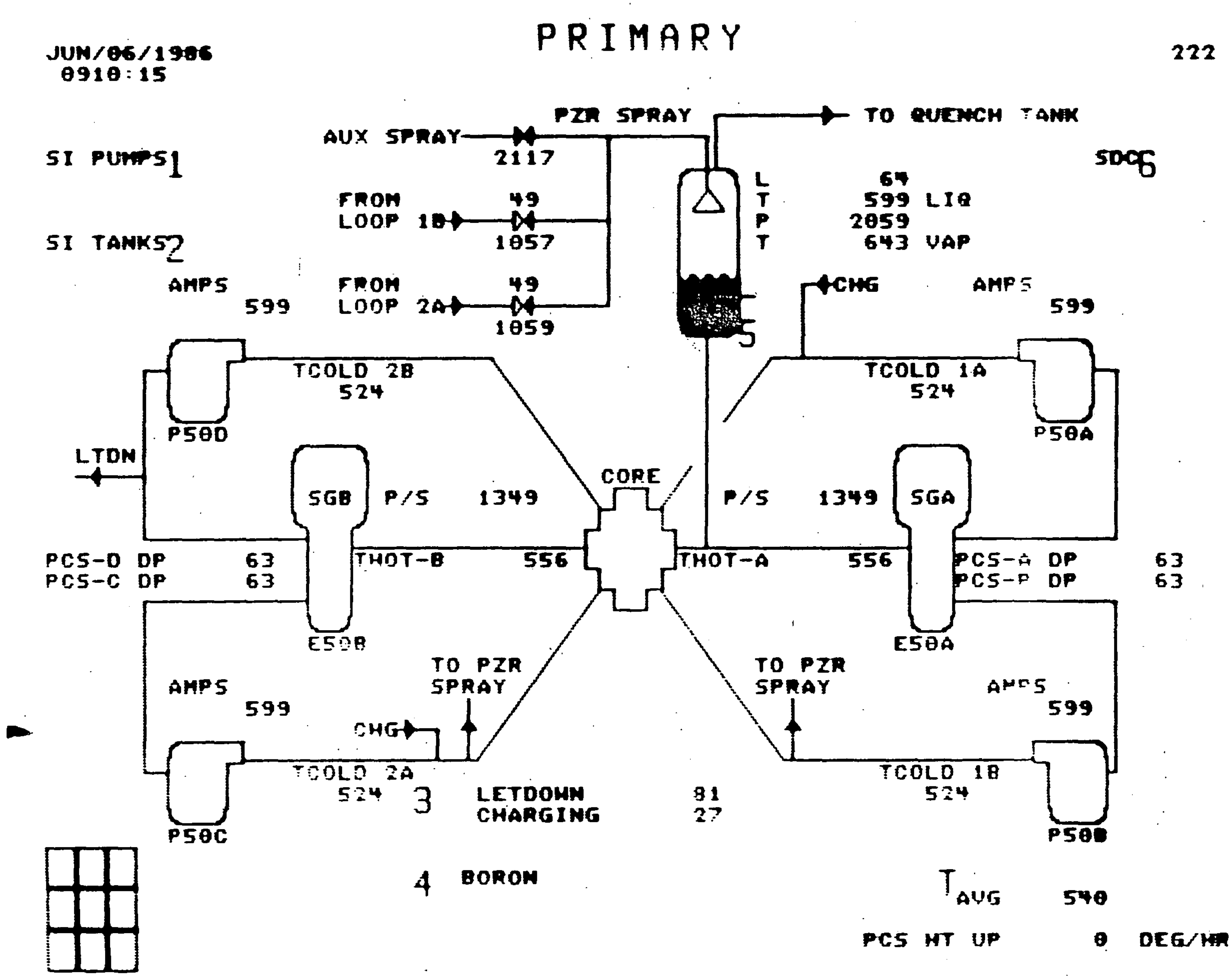
PRIM.PIIRIN LAMMONSIIRTO

MATAJAAHDYTYS TM	6

VESIKEMIA

BOORIN SAATO	3

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