INTERNATIONAL ATOMIC ENERGY AGENCY

NUCLEAR ELECTRIC Ltd.

Monitoring and Diagnosis Systems to Improve Nuclear Power Plant Reliability and Safety

PROCEEDINGS
OF THE SPECIALISTS' MEETING
JOINTLY ORGANISED BY THE
IAEA AND NUCLEAR ELECTRIC Ltd.
AND HELD IN
GLOUCESTER, UK
14-17 MAY 1996

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INTRODUCTION

The Specialists' Meeting on Monitoring and Diagnosis Systems to Improve Nuclear Power Plant Reliability and Safety, held in Gloucester, UK, 14 - 17 May 1996, was organised by the International Atomic Energy Agency in the framework of the International Working Group on Nuclear Power Plant Control and Instrumentation (IWG-NPPCI) and the International Task Force on NPP Diagnostics in co-operation with Nuclear Electric Ltd.

The 50 participants, representing 21 Member States (Argentina, Austria, Belgium, Canada, Czech Republic, France, Germany, Hungary, Japan, Netherlands, Norway, Russian Federation, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, UK and USA), reviewed the current approaches in Member States in the area of monitoring and diagnosis systems. The Meeting attempted to identify advanced techniques in the field of diagnostics of electrical and mechanical components for safety and operation improvements, reviewed actual practices and experiences related to the application of those systems with special emphasis on real occurrences, exchanged current experiences with diagnostics as a means for predictive maintenance.

Monitoring of the electrical and mechanical components of systems is directly associated with the performance and safety of nuclear power plants. On-line monitoring and diagnostic systems have been applied to reactor vessel internals, pumps, safety and relief valves and turbine generators. The monitoring techniques include nose analysis, vibration analysis, and loose parts detection. Complicated signal analysis may be involved, e.g. conversion into the frequency domain, application of correlation and pattern recognition methods, etc. Comparison to reference or "signature" information and trending are important tasks. More recently, expert system methods have been introduced in order to improve the performance of such systems. The advantages of performance, therefore, cause computers to be increasingly used to enhance monitoring and diagnostic functions to make the methods applied more user friendly and to achieve the necessary user acceptance.

Since the main goal of the diagnosis systems is the early detection of a developing mechanical and electrical deficiency, the importance for maintenance and inspection is obvious. Experience shows that due to findings of the on-line diagnosis systems, the preparation of repair actions can be considerably improved, and maintenance and inspection times can be reduced.

Monitoring and diagnosis systems can be considered as a type of operator support systems (OSS) which provide more processed, integrated information than it is available from conventional instrumentation. They guide and advise operators and enable them to make better strategic decisions during both normal and abnormal operation. They also provide a capability for supervisory management during emergency conditions. Several factors have led to increased interest in operator support systems in NPPs like e.g.:

- Increasing complexity of nuclear power plants and increasing demands for higher productivity and safety, require the operator to be more aware of plant conditions so that correct actions can be taken;
- Many of the originally installed plant information systems have come to the end of their lives. The need for replacement of these systems has stimulated a significant upgrading of their functionality for operator support;
- From a technology viewpoint, developments in computers, such as in artificial intelligence, neural networks and display technology have identified opportunities for operator support that were not possible in the past.

Some types of operator support systems received special emphasis during the meeting:

a) Fault detection and diagnosis. This alerts operators to problems and aids diagnosis before the normal alarm limits are reached. This function is also valuable when simple alarm monitoring is impractical or where complex situations cannot be revealed by alarms or alarm logic. Examples are:

- Fault monitoring of protection logic and associated electrical supplies, fuel pin failure detection and prediction;
- Detection and identification of leakage, e.g., in the primary circuit;
- Model based fault detection for components (e.g. pre-heaters) and measurement loops.

b) Performance monitoring. This function calculates and monitors the efficiency and optimum operation of main pumps, turbine, generator, condenser steam generators, preheaters, etc. to detect developing anomalies. The reactor thermal energy as well as heat, electricity and mass heat balance can be calculated.

c) Maintenance support. Several systems exist for specialists and maintenance staff. For example, vibration monitoring and analysis, loose parts monitoring and materials stress monitoring.

Systems for on-line diagnosis were attempted in the early 1980s following initial developments at the Halden project. The actual use of such systems was limited due to a number of reasons, including:

- Complexity;
- Inability to assure completeness of accident sequences and the combination of accident sequences;
- The large effort needed for maintenance.

The availability of fast, low cost computers, as well as new technologies such as expert systems have, however rekindled interest in on-line diagnosis and several such systems have been implemented or are under development.

A wide range of monitoring diagnostic systems are under development and trial at many NPPs. Advanced diagnostic systems using expert system technology and modern computer technology have been attempted and are under development. Special attention was paid during the meeting to advanced techniques which can potentially improve the ability of monitoring and diagnosis systems to enhance nuclear power plant reliability and safety, like neural network, for example.

In order to facilitate a structured discussion and not to omit important areas of interest, papers on the following subjects were considered to be within the scope of the Specialists' Meeting:

- Diagnostic and monitoring systems: state of the art, practical experience and new developments;
- Impact of diagnostic systems on NPP performance and safety;
- Advanced techniques for safety and operational improvements;
- Safety and licensing consideration, e.g. matching of new systems to safety requirements, extending plant life cycle, applicability of existing safety standards.

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ENHANCING THE FUNCTIONALITY OF REACTOR PROTECTION SYSTEMS TO PROVIDE DIAGNOSTIC AND MONITORING INFORMATION: THE ISAT[1]™ APPROACH

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ABSTRACT

The ISAT™ architecture has been successfully implemented as the Single Channel Trip System (SCTS), part of the primary protection system of Nuclear Electric's Dungeness 'B' Advanced Gas-Cooled Reactors. The system is the first computer-based protection system licensed on a UK civil nuclear reactor. The system provides protection against single channel faults resulting in high coolant gas outlet temperature. The SCTS was designed to output data at several points in the system to an Ethernet to allow checks to be made on the operation of parts of the protection system and the system as a whole. In order to monitor the performance of this shutdown system a PC based monitoring system was developed to take input as data from the Ethernet, check its integrity and then analyse the data to provide information on the state of the system and subsystems. The SCTS monitor was basically intended to alert the operator to any fault on the safety system and indicate its source, provide a diagnosis of the cause of any trip initiated by the safety system, and log the occurrences of these incidents for later inspection. The intention was also to provide accurate real-time information on the thermocouple readings and to decrease the effort required to maintain the safety system. This paper will describe briefly the development of the ISAT™ monitoring system: how its requirements were arrived at, and how the design, code and testing were carried out to ensure approval for this application. It will then go on to report how the ISAT™ monitor has performed during its time in service: how more functionality has been added over and above its original requirements. Features of additional monitors for the SCTS and other ISAT™ systems will also be described

1. INTRODUCTION

The ISAT™ system architecture, developed by AEA Technology [1], is a computer based protection system with inherent self-testing capability which provides for a fail-safe design with a high level of reliability and low spurious trip rate. The basic system was originally designed to provide a highly reliable inherently safe form of individual sub-assembly protection. An ISAT™ system was implemented as the Single Channel Trip System (SCTS) on each of Nuclear Electric's Advanced Gas-Cooled Reactors at Dungeness 'B'. The system forms part of the primary protection for single channel faults which are revealed by high coolant gas outlet temperature. The system, fully described in [1], is shown schematically in Figure 1 to identify the key components for the purpose of discussing system monitoring. The plant analogue signals, interleaved with the ISAT™ test signals, are multiplexed and digitised at the system input. The multiplexor(MUX) output is input to the trip algorithm computer (TAC) where the processing is done, a healthy or trip state determined and the appropriate signal output. The output from the TAC is a bit pattern which is passed to the vote algorithm computer (VAC). A two out of four vote is performed on the bit patterns from the four TACs and the resulting bit pattern is forwarded to the pattern recognition logic (PRL). In the case of a correct match,

[1] ™ ISAT is a registered trademark of AEA Technology

a dynamic signal is output to the pulse to direct current converter to forward the appropriate signals to the guardlines. If a mismatch occurs, in the case of a trip demand or software failure or due to equipment failure, the dynamic output is lost.

Monitoring data is output from the SCTS at two points:

- the multiplexor (the digitised raw data);
- the vote algorithm computer (the TAC data is output via the VAC; this provided a simpler implementation in the hardware).

The data is output from the SCTS via fibre optic RS232 links to a two-fold redundant ringbuffer. Here the data is identified as to its origin within the system, composed into Ethernet packets and broadcast. This data may now be gathered from the Ethernet to allow status monitoring of the MUX, TAC and VAC sub-systems individually and the system as a whole.

The monitoring system developed to capture and process this data was implemented on a 386 type PC running the MSDOS operating system. This system takes as input the sub-system data from the SCTS via the Ethernet and performs analyses that allow the operator to know the precise status of the SCTS equipment.

This paper describes: the development of the SCTS monitor system; its current usage; the future potential recognised for the system and development work that is currently underway.

2. DEVELOPMENT

The integrity level of the monitoring system is one of the key elements determining the nature of the development process. It can be seen that the monitoring system and the software it contains would be considered 'safety-related' due to the use of the monitor to oversee the operation and performance of the trip system. The particular lifecycle chosen to support this level of software development was the V model (Figure 2), as described in the STARTS Guide [2].

This model is recommended in STARTS as being suitable for any development described as 'safety-related'. The model describes the phases which are to be executed during the development process and where verification and validation are to take place. In the case of the SCTS monitor development Independent Verification and Validation (IV&V) was undertaken at each phase. Strict change control and configuration management procedures were followed throughout the development consistent with the QA programme requirement. It was decided to represent the architectural design in Yourdon diagrams and the detailed designs were expressed using Jackson Structured Programming. The development life cycle and development were supported by the following tools:

- PDF for JSP
- PASCAL compiler
- VAX CMS for configuration management.

2.1 Requirements specification

The main requirements for this monitoring system were formulated at the beginning of the development of SCTS and were subsequently refined during the development process.

The original general requirements stipulated for the monitor were as follows:

- to provide information on the status of the SCTS system equipment ;
- to drive trip and fault alarms in the control room.

The provision of these facilities required the monitor:

- to capture data at source via an Ethernet link through the ring buffers, from the MUX, TAC and VAC of the SCTS which consists of 2 suites each with four channels;

Consistent with the use of the monitor and the information it generates, the following additional features were specified for the monitor:

- to check and indicate to operators when test signals go out of tolerance;
- to administer the application of vetoes on thermocouples(used to allow maintenance);
- to diagnose the cause of a trip or fault;
- to indicate the status of all ISAT™ sub-systems;
- to display thermocouple, cold junction and test signal values in real-time;
- to display the reactor core diagrammatically and indicate those thermocouples over a set temperature.

The target hardware was a 386 type PC and the operating system was to be MSDOS.

2.2 Specification

Levels 1, 2 and 3 of the requirements specification were produced in line with the STARTS Guide [2]. This process involved close consultation with the user to define the functional requirements and to agree the basic format of the screen displays. The latter was done in conjunction with the Human Factors department of Nuclear Electric. These screens were based, in terms of content and layout, on those already in use in other reactors. Most of the functionality was derived from the display screen requirements which were used as drivers to establish the requirements. The final document to be produced was the specification of the system in conjunction with the required screen output displays.

2.3 Architectural Design

On completion of the specification the high level system design work was carried out using the Yourdon diagrammatic method. This method facilitated the system to be designed down to process level with each of the processes specified according to the functionality required and the screen display that was to be satisfied by this process. The real time aspects of the system were addressed during this exercise and the idea of cycle time for the capture of data described. The strategy for further development was planned whereby a core program would be developed which would cycle between defined states: each state had its own constraints as to the functionality that might be performed in that state. This design was verified against the requirements specification.

2.4 Detailed Software Design

For each process defined by the architectural design the lower level detail was expressed using JSP (Jackson Structured Programming). The generation of JSP design was supported by the use of the PDF tool (for a description see The STARTS Guide [2]). PDF allows the structure diagrams as described in JSP to be generated and stored electronically and also provides a limited automatic code generation facility. The detailed structure diagrams were used to generate a code structure in PASCAL. The coder would then manually insert code implementing the required operations on the data where prompted by PDF.

2.5 Implementation

The development and production of the monitor was planned as a series of builds. The initial builds dealt with the core activities such as data capture from the Ethernet and buffering of the data to allow real-time display of the data e.g. thermocouple temperature readings, status of system. Process stubs were inserted to facilitate the addition of functionality for later builds, allowing the program cycling to be tested and the base level performance to be measured.

Each build added functionality to the previous build and was designed to be as independent as practicable from other builds to aid testing. Each of the builds was associated with a process as defined in the Yourdon specification. Each build document elaborated the process function describing the data input and output requirements, and the data output to the screen. Each build consisted of several procedures each of which was programmed using PDF, and each build had its own test plan. Each build, including the associated test plans, was independently subjected to IV&V.

This method of development allowed several designer/programmers to be deployed in parallel, facilitating the optimum deployment of resources.

2.5.1 Initial Build - Data Capture Kernel

As stated before, the initial build was concerned with the capture of data from the Ethernet validation and storage of the data for input to other functions.

As all other builds relied on the initial build this was tested extensively to ensure reliability of:

(a)receipt of data;
(b)validity of data;
(c)conversion of data;

Data from all eight channels of the SCTS are placed on the Ethernet. The data from each of the channels consists of:

- data from the Multiplexor (raw digitised thermocouple and test signal values);
- data from the VAC which includes results from the TAC in the form of bit patterns.

The data are assembled in the ring buffers on a channel basis and then converted to an Ethernet package format for broadcasting. The data from the eight channels arrives at the monitor asynchronously, where it is queued and then processed.

In order to access and process these data packets it was necessary to code in assembler at the transport level of the ISO seven layer network protocol model. Checks on the validity of data were carried out and the data was then stored and pointers set up to make it available to the PASCAL program environment. (Assembly language was used as being the most direct and efficient way of bringing in the data.)

Careful testing of this part of the monitor was required in order to demonstrate that:

- all data could be identified
- lack of data from any of the channels could be identified
- consistency of the data within the packet could be assured
- the ability to switch between ring buffers was available.

3. QA CONSIDERATIONS

In order to achieve this high standard of software a quality plan was put in place at the start of the project and rigorously enforced throughout the project. All work was carried out to BS5750 Pt 1 and Pt 13. To this end procedures for change control and version control of all products were implemented. The first, a manual system and the second, using the VAX set and Code management System, provided an automated traceable record of all the project output items.

4. MONITOR OPERATION

The monitor operates in two modes:

4.1 First Mode (STARTUP)

(a) there is no data capture in operation;
(b) an initial screen stating the version is displayed;
(c) alarms are inactive.

This mode allows the operator to check that the correct version of the program is being used. This mode is the only one that allows changes to the available data constants, e.g. high temperature alarm setting, to be made.

4.2 In the second mode (NORMAL OPERATION)

(a) password entry is required to enter this mode and instigate data capture from the Ethernet;
(b) no changes may be made to data constants;
(b) alarms are active.

A main screen is displayed in both modes but with restricted choice in mode 1. This screen presents the user with a menu of options. Each option describes a particular function and includes:

(a)present data in real-time, i.e. system state;
(b)perform a diagnostic function, e.g. trip diagnosis;
(c)application or removal of a veto;
(d)display logs;
(e)display faults.

An area of the screen is reserved to annunciate faults detected on the system as they are detected. This fault detection is carried out in the data capture kernel of the system. The user navigates around the system using function keys to access the different views of the protection system offered by the monitor.

4.3 Fault Operation

The data are subjected to a series of tests which include:

- loss of Ethernet traffic;
- test signals out of tolerance;
- detection of tripped channels;
- consistency checking between TAC and VAC outputs, i.e. failure to trip, spurious trip;
- thermocouple temperature ranges (e.g. open/short circuit thermocouples);
- veto application;
- self-consistency checks of key data items.

4.4 Logging Operation

During processing the log files record the most important incidents. These log files record the following information:

- all trips that the protection system has detected and what caused the trip;
- all faults found on the protection system;
- all vetoes on the protection system.

These incidents are time stamped to trace the history of operation.
Printouts can be obtained at any time in the form of screen dumps or printouts of log files.

5. OPERATIONAL EXPERIENCE

The monitor system as described briefly above has been installed with the SCTS system on both reactors at Dungeness 'B'. The main problems encountered were as follows:

- The complexity of the final software, which provided multiple layers of screen formats, resulted in some iteration of the information displays during the period of commissioning. Some changes were required to improve the integrity and context checking of operator entered data. Other changes were made to correct minor problems that had arisen during the implementation. A number of issues arose from the differences between the agreed specification and its interpretation by the implementors and operators.

- As far as practicable the monitor is designed to reveal possible or real fault conditions. During commissioning it was found that a large proportion of the alarms logged were related to perceived failure of the data links (Ethernet from the protection system, RS232 to the alarm interface). It was found that these alarms were generally due to over prescribed checking of the data links. The alarm software on these links has now been simplified which has stopped the spurious initiation of the alarms whilst retaining the required functionality.

This monitor system allows data, concerning the protection system and the thermocouples, to be accessed at any time and replaced the manual task of testing components of the protection system, saving several man years of effort to date, providing more accurate data and replacing intrusive testing with passive analysis of data.

As indicated above the monitor was designed to report faults within the SCTS - such as test signals going out of tolerance which, for example, may be due to amplifiers failing, out of calibration. The protection system can accommodate failure of a single protection channel. The monitor notifies the operator that there is a fault on the system and will in turn allow a veto to be placed on the appropriate thermocouple thus allowing maintenance with minimum risk of spurious trip.

5.1 Health Monitoring

In addition to the SCTS monitor a separate program, using the same kernel for data capture, was developed to provide a thermocouple comparison facility. There are two thermocouples per fuel channel in the Dungeness 'B' reactors and this program is used to provide a printout of the difference between thermocouple readings, with provision to highlight those channels where the spread is greater than, for example:

- 5°C;
- 10°C;

(in this example the 5°C and 10°C values are input by the operator).

Testing of the analogue measurement channels is performed by regular and routine comparison of the four available measurements of the two thermocouples in each fuel channel. This comparison was performed by a PC-based system that monitored the data available on the Ethernet link to the main system monitor. This task was undertaken weekly to satisfy the Safety Case. The comparison check has proved to be an essential tool in monitoring the operation of the system.

This system has now been replaced by another PC based monitoring system. This "Health Monitoring" system is connected to an additional spare port on the installed Ethernet. The configuration of the trip system with uni-directional fibre optic links to the Ethernet allows such additional monitoring facilities to be added without risk of compromising the trip system reliability.

The functional requirements for the capture of the data from the Ethernet and the validation of that data were the same as for the original monitor. The additional functional requirements for this monitor included:

- archiving of all data from the SCTS channels at one minute intervals
- output of data from the SCTS to the site network running a different protocol
- a thermocouple comparison function to operate regularly on demand and alarm when thermocouples register outside set margins
- multi signal and single signal monitoring and logging
- retrieval of data stored during the archiving process

Additional non functional requirements included:

- the program to have a Graphical User Interface
- the program to be written to operate under the OS/2 operating system
- the system to be able to archive data over years

This system is different from the previous system in that the program runs under OS/2 and has a graphical user interface created using the set of APIs provided by Presentation Manager. The use of OS/2 provides significant benefits over the original DOS-based system. OS/2 is a prioritised, pre-emptive, multi-tasking system which allowed the monitor to be designed as a multi-threaded application. A thread can then be used to implement a specific function.

The development lifecycle again followed the STARTS V- lifecycle. The development was carried out using Yourdon with Ward Mellor extensions for real-time representation for the architectural design and PDF again for the low level design. For this system the language used was C and the IBM C Set++ development toolset was used which included a development environment, a trace analyser and debugging facilities

The program consists of several threads, each of which was developed separately and runs independently under the control of the operating system, according to prioritisation. A separate thread was developed to allow connection to the Ethernet at the level required, but Assembler was not required here as the facility to connect at the low level was provided by the operating system network drivers. This thread is designated time-critical and therefore will be serviced prior to others if data are arriving.

This system archives information to optical disc(s) at intervals of one minute. It can log and display all data from the SCTS for a limited period, determined by available disc space. To aid in the diagnosis of faults, data may be retrieved via a second optical disc and analyses performed on the data. The data may be retrieved in groups of signals that have something in common e.g. they share an analogue to digital board. This allows maintenance personnel to check for trend and specific information concerning the state of the system, thus reducing the requirement for proof testing. It also allows thermocouple data to be monitored over long periods of time, (months and years), which includes trips and startup and shutdown cases.

This system provides as one of its functions a continuous on-line comparison function (upgrade of function described earlier), alarming when the margins have been exceeded and displaying those thermocouples exceeding margins, in real time. The comparison system provides a printable file of the total spread in the readings of the four measurements associated with each fuel channel at intervals determined by the operator. These four readings come from the two thermocouples and thus it is possible to discern both drift in the measurement accuracy of each SCTS channel and the potential drift of one thermocouple with respect to the other.

Originally it was expected that small channel to channel variations would be masked by the random variations of several bits due to system noise (approximately 0.5°C per bit). Experience shows that it is proving possible to discern very small deviations between either the SCTS channels or between thermocouples. Figure 3 shows a typical graph of the overall measurements from a single fuel channel with no apparent problems. Figure 4 shows a larger overall spread which in Figure 5 is seen to be due to a varying deviation between the two sensors. Evaluation of this data is providing confidence that incipient faults will be revealed before they compromise system operation.

5.2 ISAT™ monitor development for Oconee

The ISAT™ system has been adapted for use on Oconee 1, a B&W PWR. A demonstration system was developed and installed and has been operational for two years. The associated system monitor was also developed to run under the OS/2 operating system using a graphical user interface, designed using Presentation Manager. The use of OS/2 allowed the use of the pre-emptive multi-tasking functions to write the RS232 interface between the plant and the monitor PC.

The DOS-based system consisted of a single execution thread, which meant that the program had to be tuned/optimised so that individual functions did not affect the program execution time and hence cause data to be lost. The program optimisation for the DOS-based system was still necessary even though it had a slower data rate of 0.5 seconds compared to the much higher data rate of the PWR system.

Under OS/2 the full memory capability is available for use compared with the old 640K limit of the DOS system. This improves programming productivity because time is not spent in improving memory utilisation, optimising program performance and does not affect possible future program upgrades. Productivity is improved with OS/2 because pre-defined APIs can be used to construct the user interface. On the DOS system the interface had to be designed from the bottom-up using assembler and Pascal. The OS/2 system uses C throughout.

6. CONCLUSIONS

The anticipated advantages were realised by operation of the monitoring system, (where any fault detected is annunciated in real-time). At any point in time the status of the protection system is known. It is also recognised that greater information may be gathered than was at first envisaged, such as data on the behaviour of thermocouples. This information is now being used to support the Safety Case.

It can be seen that when monitoring a protection system, data from all subsystems must be available and be included into the requirements of any similar system.

The use of the Ethernet system for data transmission enables the data to be accessed at many points around the plant and other dedicated analysis systems can be connected to the network allowing additional analysis. These systems can be isolated from each other, providing redundancy or diversity whichever as required.

It is now perceived that by storing the data from the instruments over a long period (in this case thermocouples), off-line analysis may be carried out to investigate the possibility of incipient faults allowing planned preventative maintenance, with the associated cost saving.

The use of the OS/2 operating system promotes multi-tasking and facilitates flexibility in the use of different drivers for data acquisition. This promotes reusability within program development and when changes and enhancements are required they can in many cases be 'bolted on' to the program, giving minimum impact on change, which preserves much of the validation status of the rest of the program.

7. REFERENCES

1. McMinn, K. W. "Dungeness 'B' Benefits from Inherently Safe Computer-Based Protection". ATOM, January/February 1993

2. "The STARTS Guide: A Guide to Method and Software Tools for the Construction of Large Real-Time Systems". Second Edition, 1987

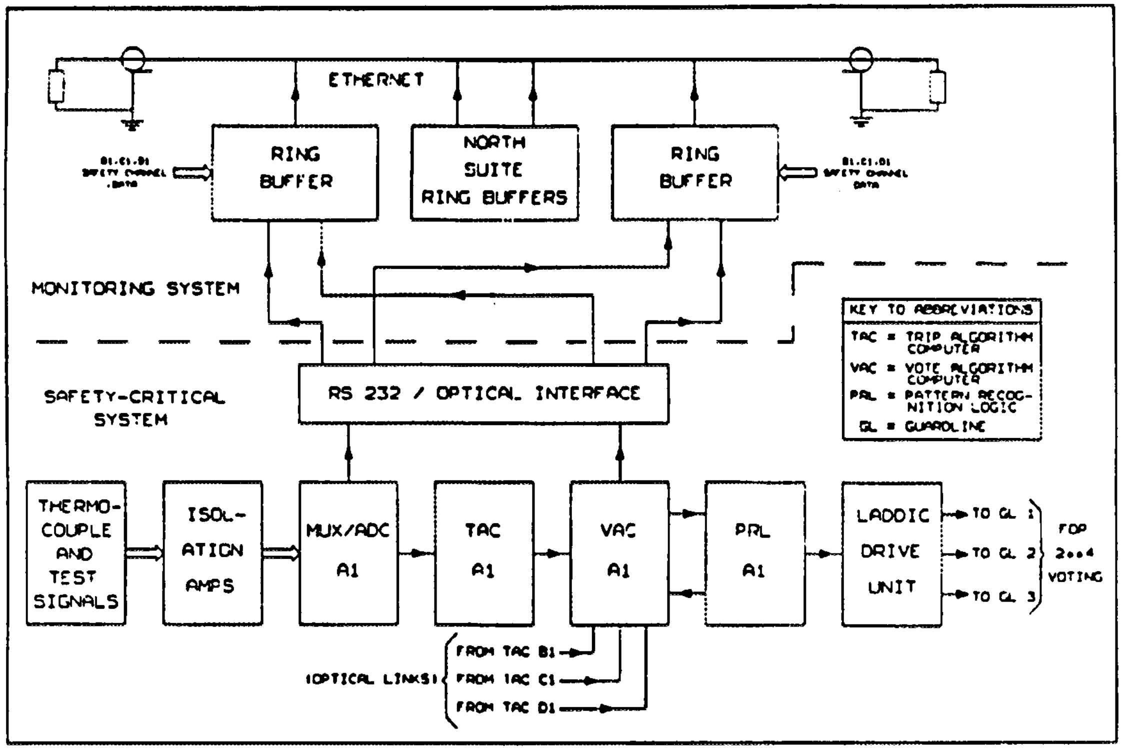

Figure 1

Schematic Diagram of the SCTS

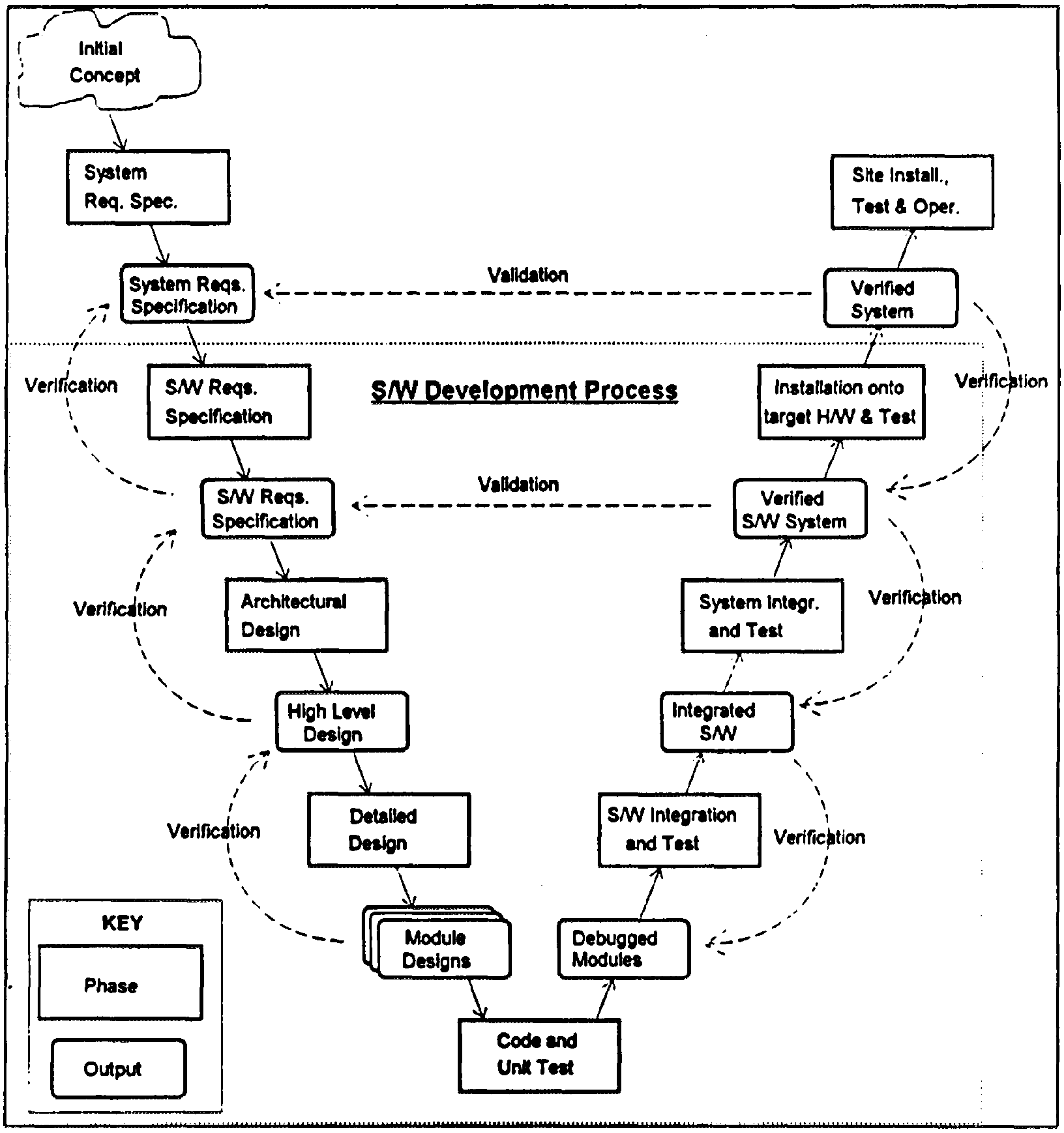

Figure 2

The STARTS Life Cycle

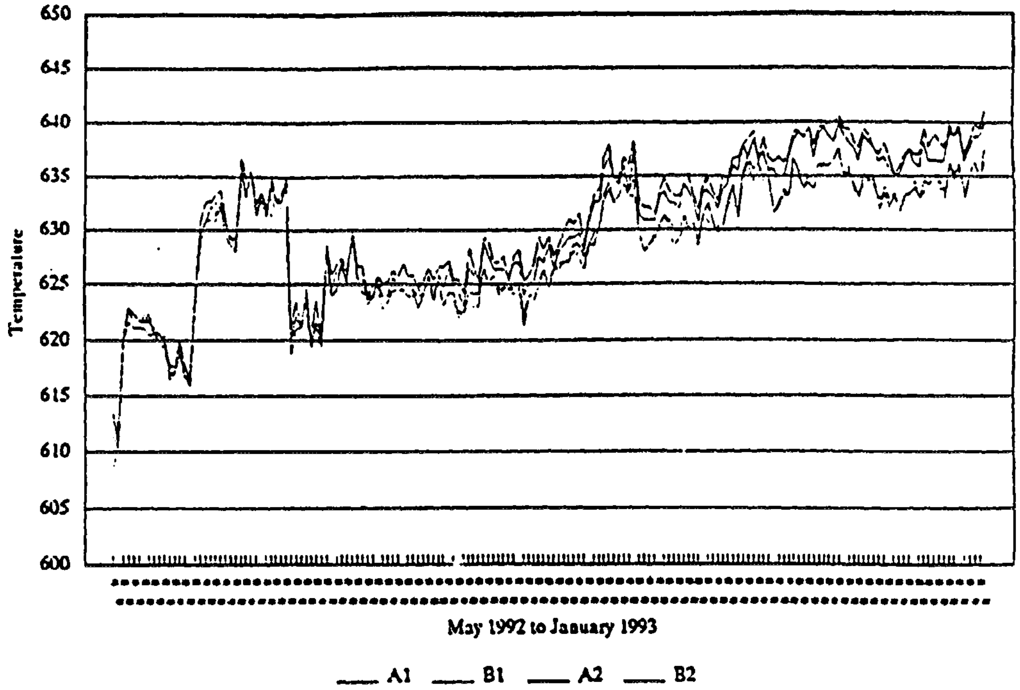

Figure 3

Variation in Temperature for Thermocouples A and B
R21 - fuel channel B14

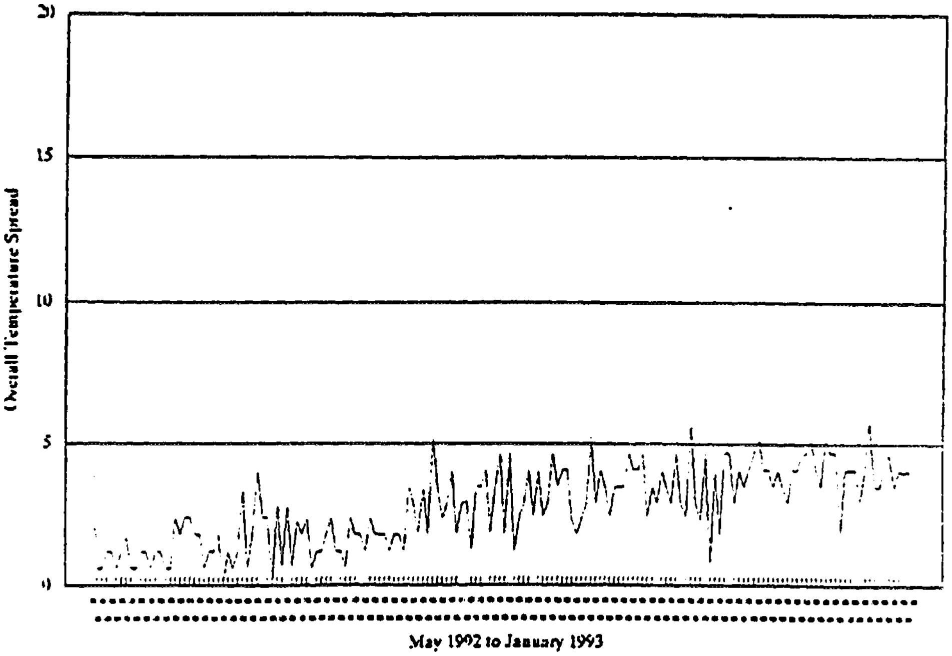

Figure 4

Spread of CGO Thermocouple Readings for R21 - fuel channel S12

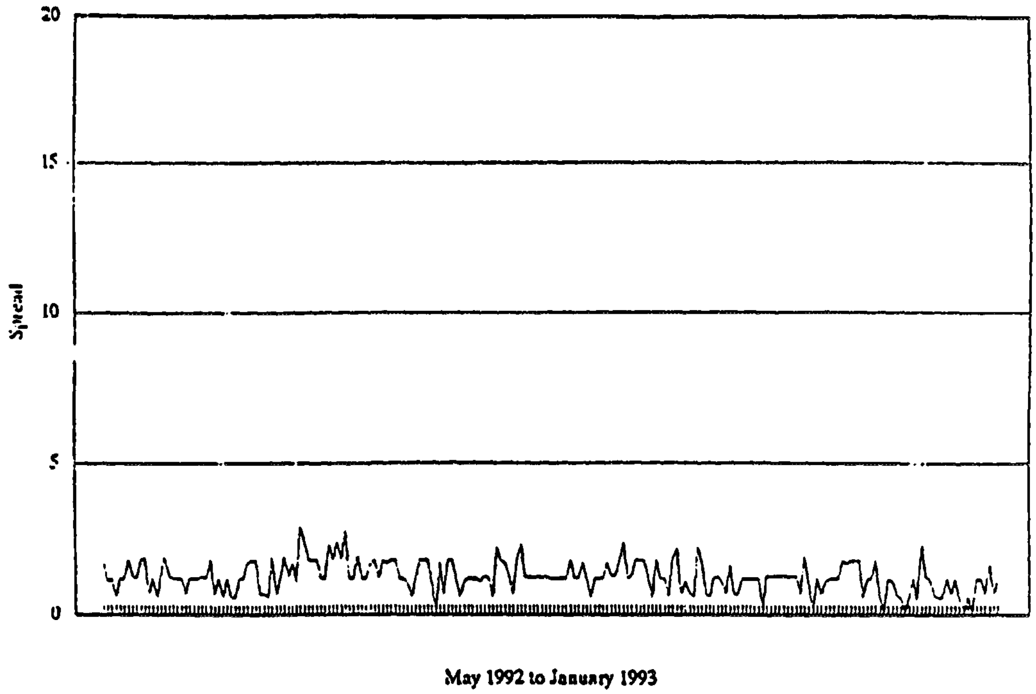

Figure 5

Spread of CGO Thermocouple Readings for R21 - fuel channel S12

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MODERATOR BEHAVIOUR AND REACTOR INTERNALS INTEGRITY AT ATUCHA I NPP

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ABSTRACT.

Atucha I is a Pressure Vessel Heavy Water Cooled Heavy Water Moderator Reactor. In this kind of reactor the moderator tank is physically connected to the primary coolant. Since neutron economy requires the moderator to be as cold as posible, it is necessary that even when physically connected, it should have a separated cooling system, which in this case is also used as a feed-water preheater, and also heat and mass transfer with primary coolant should be minimized.

This condition requires that some reactor internals are designed in principle to last the whole life of the plant. However, in 1988 the failure of one internal produced a 16 month shut down.

This incident could have been prevented but the idea that reactor internals would not have failures due to aging was dominant at that time avoiding the early detection of the failure. However, the analysis of the records after the incident showed that some process variables had changed previously to the incident, i.e., power exchanged at the moderator heat exchanger had increased.

Since the station restart up some changes in the moderator process variables and a flow rate reduction of about 10 % through the primary side of one moderator cooler were observed.

In order to understand the flow reduction and the overall behaviour of moderators parameters, two models were developed that predict moderator and moderator cooler behaviour under the new conditions

The present paper refers to these models, which together with the improvement of process variables measurements mentioned in another paper presented at this meeting permits to understand current moderator behaviour and helps to early diagnostic of an eventual reactor internal failure.

1- INTRODUCTION.

Atucha I is a pressurized vessel type heavy water reactor designed and built by KWU-Siemens in which the moderator is physically connected to the primary coolant. Since neutron economy requires that the moderator should be as cold as possible, it has a separated cooling system which is also used as a feedwater preheater. On the other hand, heat and mass transfer between both systems should be minimized.
A simplified draw of the Primary Heat transport System is shown in Figure 1, while some design variables and operating parameters are presented in Table I.
In 1988 a failure of one reactor internal, a coolant channel, produced a 16 month shutdown and addressed different groups improving the capability of understanding the moderator behaviour and surveillance of the related variables, problem that, due to the complexity of the system represents a challenge. The incident probably could had been detected before, because, according to some records, some process variables had started to change some months before. Nevertheless , the philosophy at that time was that structural components had been designed for the whole life of the station and were practically damage free.
The purpose of this paper is to present two models, that have been developed and gradually validated along several years and finally will be installed as an on-line moderator system surveillance resident in the station process computer.

2- MODERATOR SYSTEM BEHAVIOUR.

The moderator system was nodalized according to the dash-enclosed sector of Figure 2. Basically, the model is based in the one proposed by the designers with some outstanding improvements.

2.1

The main unknown variable is the flow exchange rate between the moderator and the coolant through the moderator tank lid designated as GS . This parameter will be also power dependent , then it will be correlated vs. the difference between D2O density evaluated at TMEZ and D2O density evaluated at TRSUP.
The values of α, β, GI, TSM and W are based in previous calculations or measurements. Then , the values of the unknown variables GS, HTINF and HTMEZ are found by solving the following mass and energy balances for a thermal power plant set of variables recorded in 1977, i.e., when the station was in its primitive conditions. It should be pointed out that GI and β have been slightly changed in order to obtain a consistent GS vs. densities difference curve in which GS should decrease with the densities difference and never admits negative values.

$$GI * HTER + GS * HTSR + W * \alpha + \beta * DT + QM * HTEM = QM * HTSM + (GI + GS) * HTMEZ \qquad (1)$$

$$GI * HTMEZ + QM * HTMEZ + GS * HTSR = QM * HTSM + GI * HTMEZ + GS * HTMEZ \qquad (2)$$

$$GI * HTER + QM * HTEM = (QM + GI) * HTINF \qquad (3)$$

Also, it was assumed that, because of the symmetric condition of both moderator loops, average values of the temperatures could be used for the calculations:

$$DT = (TSR + TER) / 2 - (TMEZ + TINF) / 2 \qquad (4)$$

$$TER = (TER1 + TER2) / 2 \qquad (5)$$

$$TSR = (TSR1 + TSR2) / 2 \qquad (6)$$

$$TEM = (TEM1 + TEM2) / 2 \qquad (7)$$

$$QM = (QM1 + QM2) \qquad (8)$$

Once equations (1) to (3) are solved for GS, HTINF and HTMEZ, the corresponding temperatures and densities are found and, as it was explained above GS is correlated against the densities difference:

$$TINF = f (HTINF)$$

$$TMEZ = f (HTMEZ)$$

$$GS = D (TMEZ) - D (TSR) \qquad (9)$$

The curve given in equation (9) is shown in Figure 3.

2.2

Once the values of GS have been established through the calculations depicted above a whole model of the moderator system is set up by follow Figure 2. The model will be now capable of allowing for a possible lack of simmetry in different parameters such as the moderator flow rate in each loop, heat exchangers behaviour, etc. The following equations have then to be solved and the Code Simod [1] provides the sought values of TSM, TEM1, TEM2, T1,T2 PM1 and PM2.

$$QM1 * (HTSM - HTEM1) = QM2 * (HTSM - HTEM2) = GI * (HTER - HTMEZ) + GS * (HTSR -HTMEZ) + W * \alpha + \beta * DT \qquad (10)$$

$$QM1 * (HTSM - HTEM2) = GH2O1 * (ENT1 - ENTF1) \qquad (11)$$

$$QM2 * (HTSM - HTEM2) = GH2O2 * (ENT2 - ENTF) \qquad (12)$$

$$GH2O1 * (ENT1 - ENTF) = UA1(GH2O1) * DMLT1 \qquad (13)$$

$$GH2O2 * (ENT2 - ENTF) = UA2(GH2O2) * DMLT2 \qquad (14)$$

$$GI * HTER + QM1 * HTEM1 + QM2 * HTEM2 = (GI + QM1 + QM2) * HTINF \qquad (15)$$

The Code requires the following input data :
TF, QM1, QM2, W, TSR1, TSR2, TER1, TER2, GH2O1, GH2O2, α β and GI(DD) whereas the moderator heat exchanger overall heat transfer coefficient was obtained from the new data adquisition and processing system [2].
Then, if no other alterations have occurred, by a careful measurement of the process variables which in turn are fed into the Code and through its results it is possible to compare the present situation to the 1977 operative status.

2.3 Comparison with observed data.

Due to the fouling in the S.G's and Moderator cooler (where there are also clogged tubes, as it will be explained in the next paragraph) changes in the moderator thermal parameters have been experimented.
It was found that the best way to check the performance of the moderator-cooler heat and mass barrier was to compare the moderator power vs.the average moderator temperature.
Code runs for a range of total reactor power between 95 and 102 % predict a power coefficient for the moderator of 0.5 Mw per % of reactor thermal power and 0.5 Mw per degree of increase of primary mean temperature.
All the analysis has been done close to 100% power because the station operates in that condition most of the time.
Comparison with data observed in the plant show differences no higher than 1.5 Mw which is lower than the measurement error.

3.-MODERATOR HEAT EXCHANGER BEHAVIOUR.

One of the consequences of the 1988 incident was that some debris of the fuel channel insulation foil were transported by the flow to the heat exchanger #1 inlet chamber producing a flow rate decrease through that device. Besides, a gradual fouling process has been developed along the years producing an extra decrease in heat transfer capability.
It should be noted that the flow decrease was not constant along the time, rather it was observed when a periodic test that perturbates the flow is performed.
In order to understand the moderator cooler behaviour, a hydraulic and thermal model for the moderator piping and moderator cooler was set up.

3.1 Hydraulic Moderator Heat Exchanger Model

The mechanical energy balance has been set up for the loop 1 of the Moderator system (i.e., the one suspected of being partially plugged) for both, 1977's and the present conditions .

$$C1 * (Q10 + Q20)^2 + C2 * Q10^2 + C1 * Q10^2 / N0^2 = hb10 \qquad (16)$$

$$C1 * (Q11 + Q21)^2 + C2 * Q11^2 + C1 * Q11^2 / N1^2 = hb1 \qquad (17)$$

Adopting Q10 = Q20 for the same reasons mentioned in 2.1 and defining the following ratios :

$X = Q11 / Q10$

$Y = Q21 / Q20$

$r = N1 / N0$

a relation between r, X and Y can be written :

$$r^2 = \frac{X^2}{1 - \frac{C_2\, n_0^2}{C_1} * \left(\frac{hb_{10} - hb_1}{C_2\, Q_{10}^2} - 1 + X^2 - \frac{4\, C_1}{C_2} + \frac{C_1\, (X+Y)^2}{C_2} \right)} \qquad (18)$$

The Hydraulic resistance coefficients C1, C2 and CI have been calculated from data originated in the Design Manual and assuming fully turbulent flow (i.e., C is not a function of the Reynolds number).
Since the friction factor doesn't change substancially in the tubes for different moderator flow rates, it is possible to write:

$$\Delta P11 / \Delta P10 = [(QM1 * N0)/(Q0 * N1)]^2 \qquad (19)$$

Then, rearranging (19) it is found that:

$$(N1/N0)^2 = (Q1/Q0)^2 * \Delta P11 / \Delta P10 \qquad (20)$$

3.2 Thermal Model.

Consistently with the hydraulic model, it was also assumed here that a tube is either completely plugged or not plugged.
Since it can be easily shown that for the primary side heat transfer coefficient there is almost no dependency with the primary side flow rate (in the whole operating range of the moderator flow rate), all the observed thermal capacity decrease is attributed to an area reduction.

Therefore :

$$R0 / R1 = A1 / A0 = N1 / N0 \qquad (21)$$

Finally, data obtained for different flow conditions where ΔP across the heat exchangers was measured connecting ad-hoc D.P. Cells , sketched in Figure 4, and thermal resistance coefficients obtained by the on-line resident computer software confirmed the validity of the proposed model.

4. CONCLUSIONS.

Two models that interpret (i) Atucha I moderator-coolant interrelation and (ii) moderator heat exchanger behaviour have been presented and explained by thermal and mechanical energy balances along the moderator circuit.
The first model has been able to understand and predict the power transmited by moderator coolers and correlate it with reactor internals proper performance.
The hydraulic model for moderator loops based in total plugging of a postulated number of tubes suitably interprets changes in the moderator flow rate and is consistent with variations in the overall heat transfer coefficient and pressure drop measured across the tubes bundle.

5. REFERENCES.

[1] Modelo para el comportamiento del moderador de la C.N.A. I. M.Chocrón, Ma. del C. Raffo Calderón y G.Urrutia. Informe Técnico Depto. Química de Reactores AI/25/90.
[2]Process Variables Consistency at Atucha I NPP.M.Aparicio, E.Arostegui, P.Herzovich, G.Urrutia, J.Wenzel. Presented at this Meeting.

6. NOTATION

α	Moderator radiant energy absorption coefficient (%)
β	Primary coolant-moderator heat transfer coefficient (Mw/°C)
ΔP	Moderator heat exchanger pressure drop (ata)
A	Moderator heat exchanger transfer area (m^2)
C_1	Inlet pipe hydraulic resistance coefficient
C_2	Outlet pipe hydraulic resistance coefficient
C_I	Moderator heat exchanger hydraulic resistance coefficient

D	Density (Kg/m^3)
DD	Density difference defined by equation (9) (Kg/m^3)
$DMLT_i$	Moderator heat exchanget Logarithmic mean temperature difference (°C)
DT	Temperature difference defined by equation (4) (°C)
ENTF	Feedwater moderator heat exchanger inlet enthalpy (MJ/tn)
ENT_i	Feedwater moderator heat exchanger oulet enthalpy (MJ/tn)
$GH2O_i$	Feedwater flow rate (tn/h)
GI	Flow rate exchanged at the Moderator Tank bottom (tn/h)
GS	Flow rate exchanged at the Moderator Tank top (tn/h)
hb	Moderator pump height (m)
HTEM	Moderator inlet enthalpy (MJ/tn)
HTER	Primary side inlet enthalpy (MJ/tn)
HTINF	Moderator mixing enthalpy according to Fig. 2 (MJ/tn)
HTMEZ	Moderator mixing enthalpy according to Fig. 2 (MJ/tn)
HTSM	Moderator outlet enthalpy (MJ/tn)
HTSR	Primary side outlet enthalpy (MJ/tn)
N	Moderator heat exchanger tubes number
PM_i	Moderator heat exchanger power transmited (Mw)
QM_i	Moderator Flow Rate (tn/h)
R	Moderator heat exchanger overall thermal resistance (°C/Mw)
ROM_i	Moderator heat exchanger average feedwater density (Kg/m^3)
TEMi	Moderator inlet temperature (°C)
TERi	Primary side outlet temperature (°C)
TF	Feedwater moderator heat exchanger inlet temperature (°C)
T_i	Feedwater moderator heat exchanger outlet temperature (°C)
TINF	Moderator mixing temperature according to Fig. 2 (°C)
TMEZ	Moderator mixing temperature according to Fig. 2 (°C)
TSM	Moderator outlet temperature (°C)
TSR_i	Primary Side Outlet Temperature (°C)
TSRi	Primary side Inlet Temperature (°C)
UA	Moderator heat exchanger overall heat transfer coefficient (Mw/°C)
$Visc_i$	Moderator heat exchanger average feedwater viscosity (Kg/m sec)
W	Nuclear Power (Mw)

Table I
Some Design Parameters of Atucha I NPP

Primary Coolant and Moderator fluids	D2O
Power transferred through the Steam Generator (Mw)	2 * 535
Power transferred through the Moderator coolants (Mw)	2 * 58
Primary Side Flow Rate (tn/h)	2 * 10000
Moderator Flow Rate (tn/h)	2 * 800
Primary Side Reactor Inlet Temperature (°C)	265
Primary Side Reactor outlet Temperature (°C)	300
Moderator Inlet Temperature (°C)	141
Moderator Outlet Temperature (°C)	198
Secondary Side Flow Rate (tn/h)	2 * 930
Feedwater Inlet Temperature (into the Moderator Heat Exchangers) (°C)	120
Feedwater Inlet Temperature (into the Steam Generators) (°C)	173
Steam Pressure (ata)	44
Steam Generator Area (m^2)	2 * 3454
Moderator heat exchangers Area (m^2)	2 * 683
Moderator heat exchanger tubes number	1049

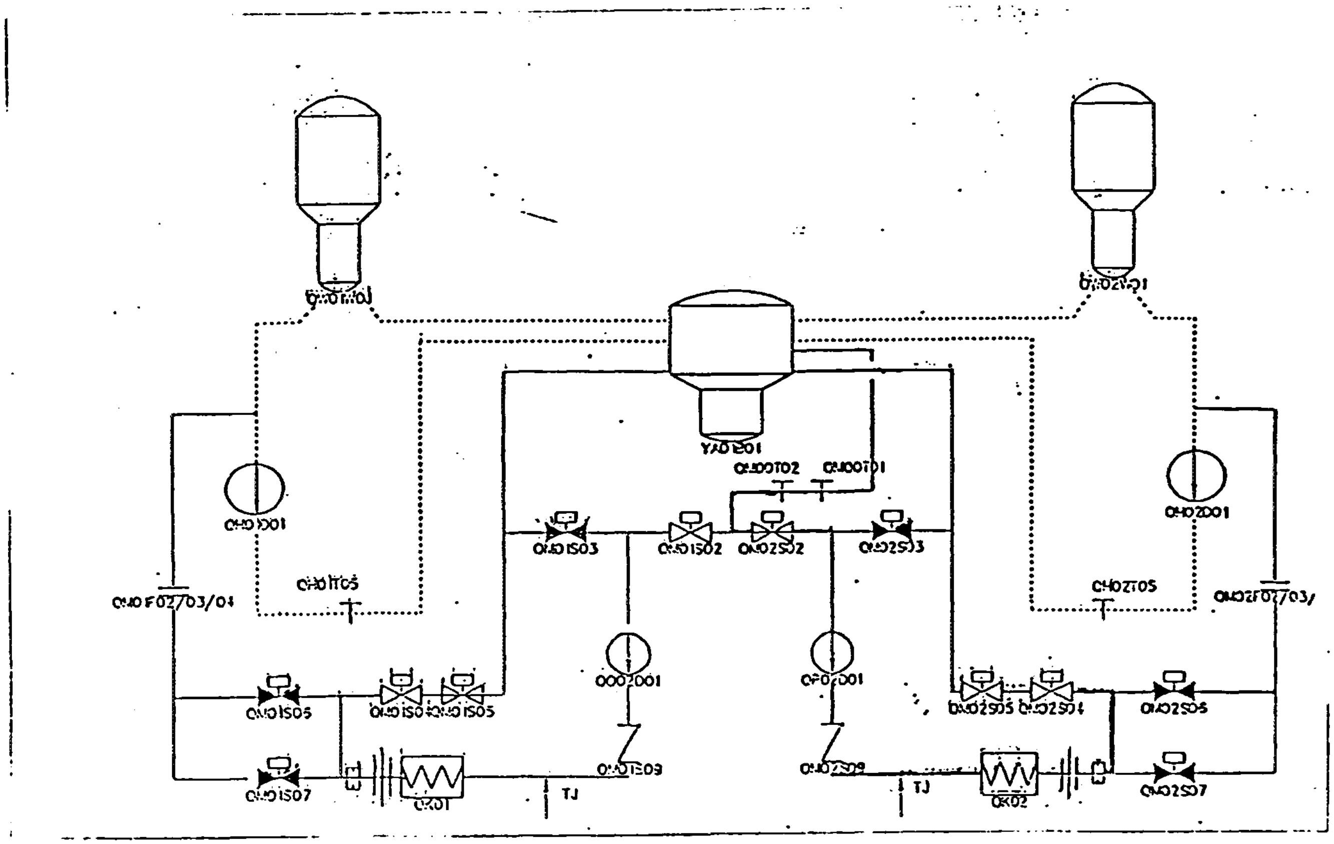

Figure 1

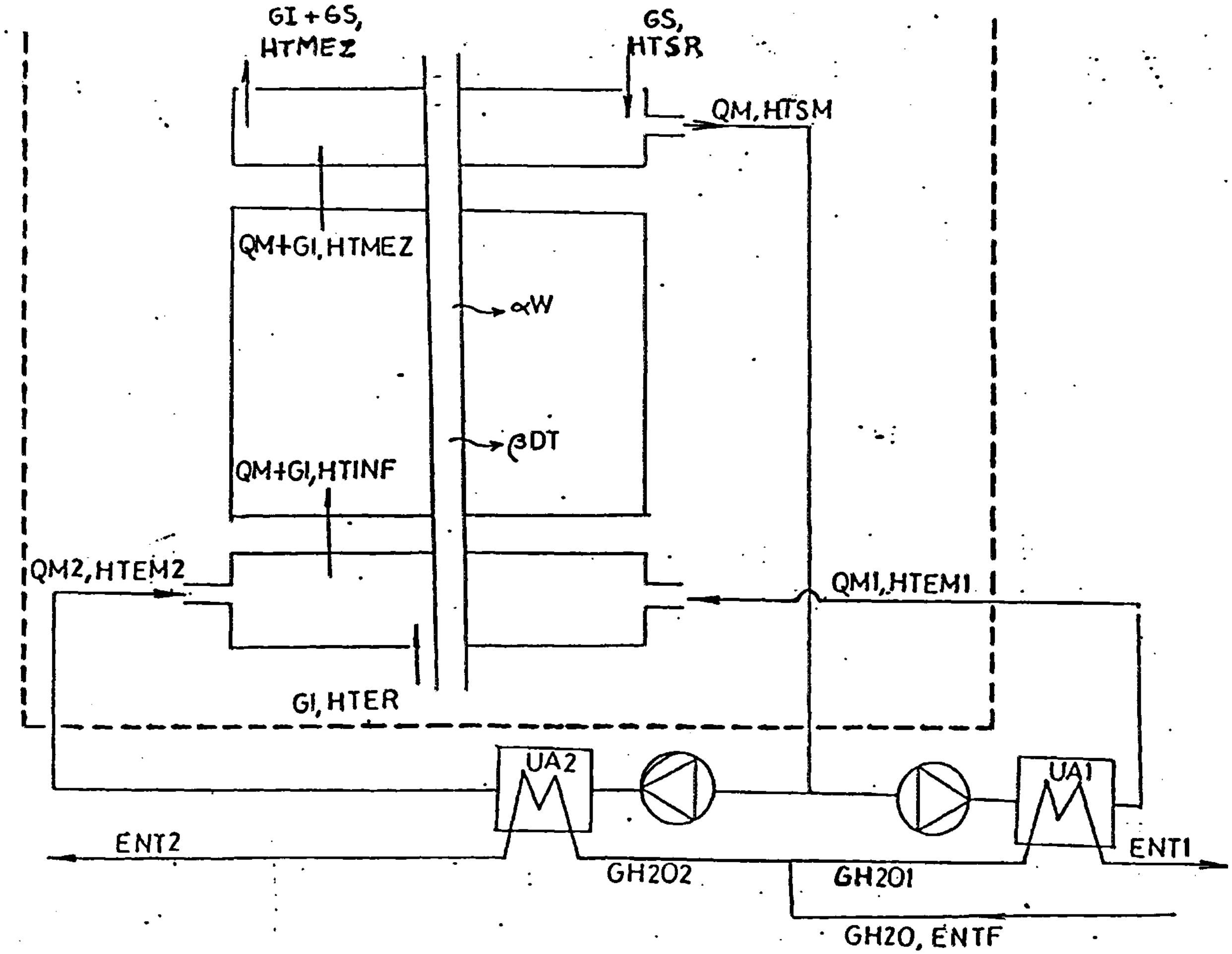
GI + GS,
HTMEZ
GS,
HTSR
QM, HTSM
QM+GI, HTMEZ
αW
βDT
QM+GI, HTINF
QM2, HTEM2
QM1, HTEM1
GI, HTER
UA2
UA1
ENT2
GH2O2
GH2O1
ENT1
GH2O, ENTF

Figure 2

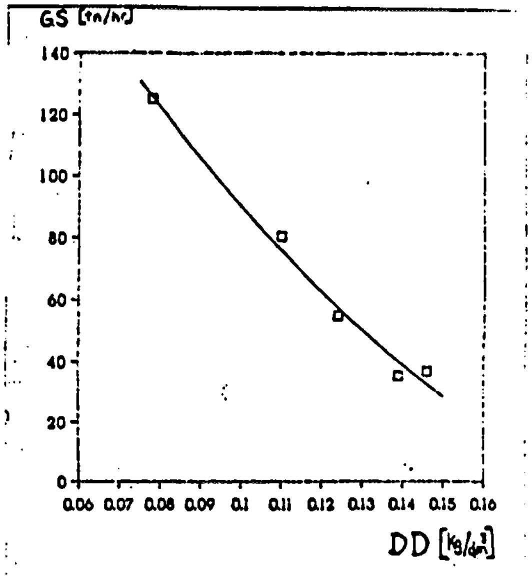

Figure 3

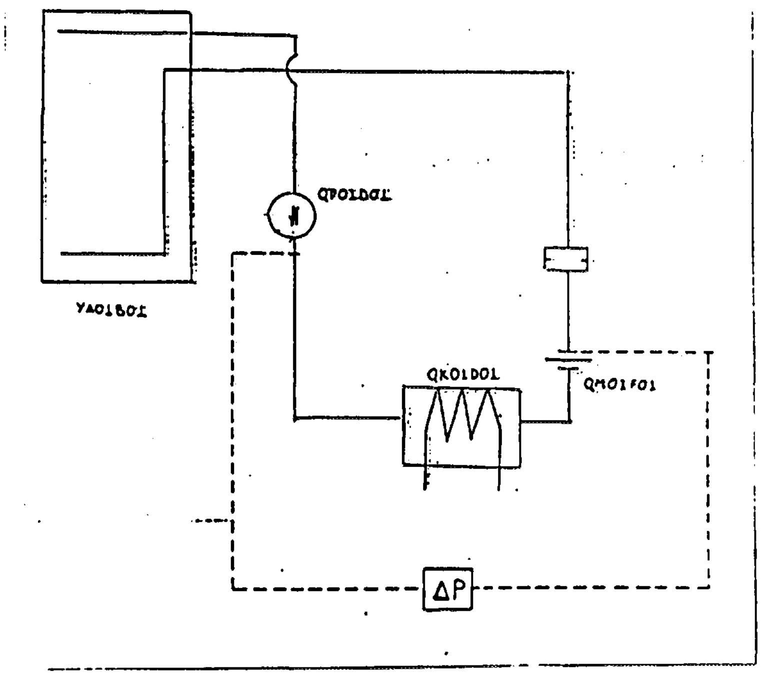

Figure 4

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Experiences With an Expert System Technology for Real-Time Monitoring and Diagnosis of Industrial Processes

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ABSTRACT

The complexity of modern industrial processes and the large amount of data available to their operators make it difficult to monitor their status and diagnose potential failures. Although there have been many attempts to apply knowledge-based technologies to this problem, there have not been any convincing successes. This paper describes recent experiences with a technology that combines artificial intelligence and simulation techniques for building real-time monitoring and diagnosis systems. A prototype system for monitoring and diagnosing the feedwater system of a nuclear power plant built using this technology is described. The paper then describes several interesting classes of failures that the prototype is capable of diagnosing.

1.0 Introduction

Industrial processes -- such as ones for producing electricity, processing petrochemicals or manufacturing new products -- constitute the economic engines of modern societies. Economies thrive or flounder depending on how well they can compete and continuously update their industrial processes.

Beyond advances in control theory and engineering, materials, nuclear technologies and the like, industrial processes are currently undergoing fundamental change because of the introduction of information technologies. Such technologies range from networking and advanced real-time data gathering techniques, to high level processing of incoming plant data for purposes of monitoring, production optimization and emergency handling.

This paper focuses on the application of AI and advanced simulation techniques in the development of a technology for building real-time monitoring and diagnosis systems for industrial processes. The paper describes some of the capabilities of a system developed by a joint Industry-University research project named APACS (Advanced Process Analysis and Control System) funded by the Canadian Federal Government and participating industry through PRECARN Associates Inc. The project included as industrial participants potential customers of the technology (Ontario Hydro, Shell Canada, Stelco) as well as potential exploiters (CAE Electronics and Ontario Hydro).

The milestones of APACS include developing a series of prototype systems which together assist an operator monitor plant data and diagnose plant faults. The prototypes have been built for the feedwater system of Ontario Hydro's Bruce B Nuclear Generating Station (NGS). Feedwater systems supply hot, pressurized, demineralized water to plant boilers under normal operating conditions, including plant start-up and shutdown. Such systems were chosen as test case for the project because they constitute a pervasive component of many industrial processes, which the APACS technology is intended to serve.

The rest of the paper consists of a description of the APACS architecture followed by a discussion of several interesting classes of failures that APACS can detect. Finally, the paper describes the status of the APACS project. A companion paper [10] describes a slightly earlier APACS with an emphasis on the lessons learned through the various prototyping phases.

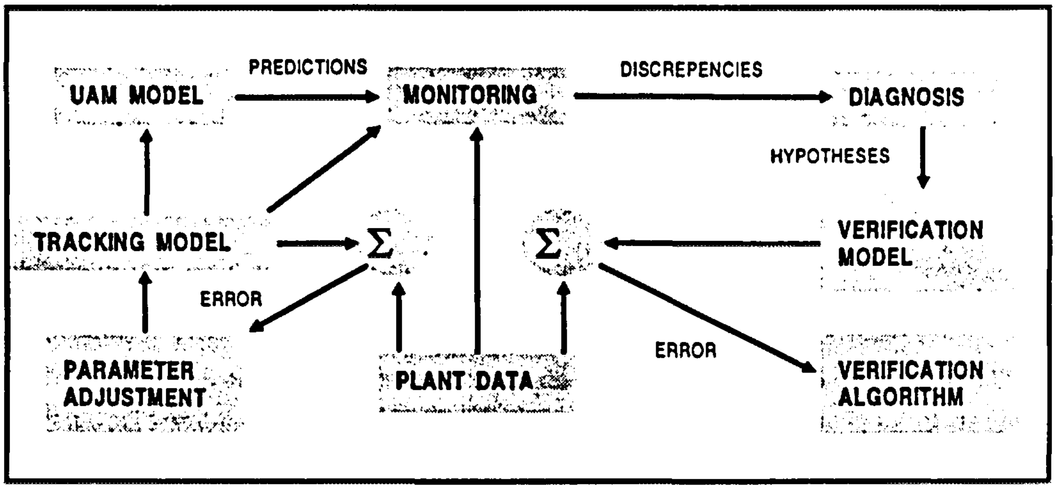

Figure 1: APACS Functional Organization

2.0 APACS Function and Architecture

2.1 Functional Architecture

The overall function of APACS is to monitor the plant and, whenever there is a problem that APACS is designed to handle, inform the user as soon as possible. This is accomplished by continuously comparing the readings from sensors in the plant with values generated a numerical simulation and reporting and explaining any discrepancies should they occur. The overall function is decomposed into the functions illustrated in figure 1. Plant data is used in three ways: first, it is compared to predictions from a numerical model called the *tracking model* whose parameters are continuously modified by a parameter adjustment algorithm. The changed parameters are periodically passed to the *unadjusted (UAM) model.* Second, plant data is compared to the predictions of the UAM Model in the *Monitoring* component which generates symbolic descriptions of discrepancies called *triggers*. The *Diagnosis* component then generates one or more fault hypotheses that might explain these discrepancies. Finally, plant data is compared with the output of the *Verification* model incorporating the candidate fault hypotheses and the errors are used by the *Verification Algorithm* to compute scores which allow the selection of the best hypothesis.

The simulation of the hydraulic network (the feedwater system) uses an admittance matrix method [8] to compute internal pressures from measured values at the boundaries of the subsystem and admittances calculated from the pressures at the previous time step. In addition to measured values, the boundary conditions include real-time control signals from the plant control computer. The tracking algorithm uses an iterative numerical approximation algorithm [9] to calculate changes in parameters to the model in order to reduce the differences between the plant and the corresponding outputs of the model. The algorithm treats the model as a black box and can therefore be implemented using an existing simulation, a simulation built from standard model libraries, or a simulation generated by a graphical simulation building tool. Small changes in these parameters allow the model to adapt to an always changing plant and to compensate for the inevitable inaccuracies in the model. The changed parameters are periodically supplied to the UAM to ensure that it is close to the plant. Large changes in the parameters generally indicate that there is a problem in the plant.

Monitoring creates events in response to significant changes in the differences between *UAM* outputs and sensor readings and in response to significant changes in the parameter values calculated by *Tracking*. It also creates events in response to threshold crossings of certain sensor readings.

The monitoring component is a real-time knowledge-based component [11] and is implemented using a combination of C++ and a forward chaining rule language. In order to avoid unnecessary attempts to match rule conditions, the monitoring knowledge is divided into modules, each of which has a list of triggers that specify under what circumstances certain conditions are to be checked. A trigger refers to a data value and a description of the interesting circumstances. This description can be as simple as "every frame" or as complex as "whenever the running rate of change equals 0." Triggers improve efficiency by limiting the occasions on which conditions are checked.

Whenever the circumstances described by a trigger are true, the conditions associated with the trigger are evaluated. Conditions specify computations that result in symbolic values. If the value of a condition changes, a corresponding feature is asserted into the rule engine's working memory and rules may fire in response to these features. A condition might be used to create features when the rate of change of some input value enters some new qualitative range. An example is a condition that labels the slope of a boiler level as one of decreasing, flat, or increasing. Conditions include a property called persist time that is designed to suppress spurious outputs. If the persist time is non-zero, the condition must be true for at least the specified time before a feature will in fact be created. The thresholds used in conditions can be either numbers or objects that specify decaying values. The idea here is that in certain circumstances, for example, changes in plant state, some rule will change the width of the threshold. This width will then decay as time passes. This provides a mechanism for changing thresholds in circumstances such as plant manoeuver, where the transient changes allow larger than usual variations in values. This is used, for example, to allow boiler levels to move a greater than usual distance from their set-points during major changes of the plant. All of the objects, the rules, conditions, etc. describing the monitoring task for a particular plant are stored in the CKB.

Diagnosis computes a qualitative causal explanation for the events output by *Monitoring*. In abnormal situations this explanation will include a fault hypothesis that indirectly or directly explains the *Monitoring* outputs. *Diagnosis* operates by chaining backward from events, hypothesizing immediate causes for events using generic rules that propagate changes over linked components in a plant. For example, a rule might state that an abnormal increase in flow at component X may be caused by a corresponding increase in flow at a component linked to X. Causal chains from different input events are joined when they reach a component in common - at such times constraints on the times of events are propagated by a temporal reasoner. A fault hypothesis is generated when a single failure event is the root of causal chains leading to all of the symptoms.

In both Monitoring and Diagnosis, the rules are written in terms of *classes* of components. The result of this is that the complexity of APACS grows with the number of different types of components, not the number of components in the modeled system. Experience has shown that the number of rules grows linearly with the number of classes of component.

Verification is used by *Diagnosis* to select between competing fault hypotheses. For each fault hypothesis, the model is modified to account for the failure and the outputs are computed for a period of time following the hypothesized time of the fault. These outputs are compared to the recorded history of the sensor readings and a measure of the differences over some interval is computed. The hypothesis having the smallest value for the measure of the difference is the ultimate output of APACS. Since Diagnosis can only compute approximate times and severities for a hypothesized fault, Verification searches a space of different times and severities using a simple hill climbing algorithm that identifies the combination with the best score.

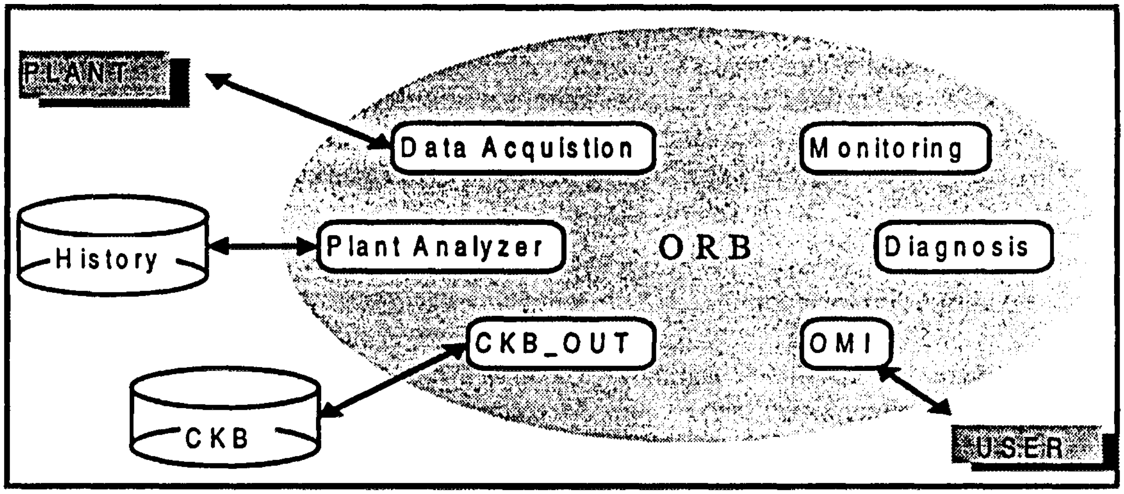

Figure 2: System Architecture

2.2 System Architecture

The architecture of the system implementing the functions described above is illustrated in figure 2. The gray oval contains the components that implement the functions and shows them communicating through a commercial object request broker (ORB). Messages are knowledge base objects represented as instances of C++ classes. Components inform each other of the classes of objects in which they are interested and each component distributes objects to components as per their expressed interests. In this architecture, each function can be implemented as a separate process using the most appropriate language and run-time environment. Also, functions can be distributed across several computers. Since communication uses structured objects that are instances of a common schema (that is, instances of C++ classes), there is no need to parse messages.

Figure 2 shows components corresponding to the data acquisition, monitoring, and diagnosis functions described above. The UAM, Tracking, and Verification functions are grouped together as a component called the Plant Analyzer since they are implemented as one program containing the numerical model of the plant. They do however run as three different processes. The plant analyzer components have a private database in which they store the history of plant sensor values so that they can be used for verification.

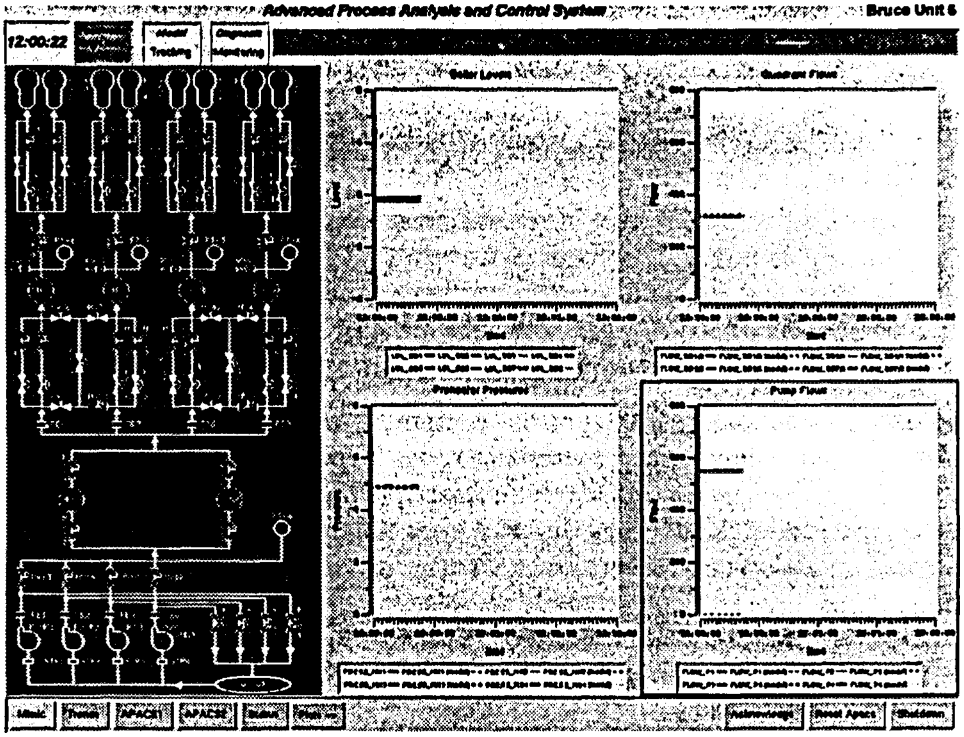

Figure 3: The APACS OMI

The CKB_OUT component communicates with an object-oriented database called the *common knowledge base (CKB).* All domain-specific knowledge is stored here and supplied to the components via CKB_OUT and the ORB. A common knowledge base serves two purposes: first, it guards against redundant and inconsistent knowledge, and second, by storing domain-specific knowledge, it is the place where most changes need be made in moving APACS to a different plant or process.

The *OMI (operator-machine interface)* is the component that manages interaction with the user. Figure 3 below shows a screen dump. The main functions of the OMI are to 1) give an operator some indication of what the APACS components are doing, 2) indicate to the user if there is a possible problem when monitoring detects significant changes or discrepancies, 3) when a fault is identified, provide the identity of the fault and some indication of the system's reasoning, and 4) provide users with tools for displaying sensor data and model outputs so that they can check for themselves that APACS has correctly identified the failure. The OMI therefore has windows that display APACS activity (top left), a message window (top right) for displaying text, a plant schematic (left) on which the faulty component can be highlighted, and several areas for plotting sensor and model outputs. The OMI has several pages, one of which can display the causal relationships between the faults and the symptoms. The design was guided with reference to *ecological interface design* as described in [19].

This architecture combines to form the APACS Framework for building process monitoring and diagnosis systems. The framework supports adaptation to new problems in two ways: first, domain-specific knowledge, stored in the CKB, is separate from the knowledge encoded in the components for performing inferences, and second, the communications architecture makes it simple to add, remove, or replace components as is appropriate for the new problem. For example, one might want to replace the OMI when moving to a different plant or process.

4.0 Classes of Failures

4.1 Introduction

This section provides a brief description of several interesting class of failures successfully addressed by APACS. Thus far, the data that is being used is to test APACS has been generated from high fidelity simulations of the plant that are used for training operators and solving design problems. However, the data collection component of APACS has now been installed on a pilot basis on one unit of the Bruce B NGS and preliminary analysis of the resulting data has shown that there is a good match.

APACS models approximately 150 specific equipment malfunctions including pipe breaks, heat exchanger fouling, level control and motorized valve failures, and transmitter failures. The plan for evaluating APACS includes generating several instances of those failures that are modeled in the training simulator at different severities and under different plant conditions. The following sections briefly discuss transmitter failures, subtle valve failures, dual failures in series, and failures outside of the feedwater system.

4.2 Transmitter Failures

APACS successfully diagnoses several kinds of transmitter failures in the feedwater system; these consist of two classes of failure at each of four pressure transmitters and each of eight flow transmitters. The diagnosis of these failures does not involve the causal reasoning of the diagnosis component since significant transmitter failures result in control actions that can cause dramatic divergence between the plant and the simulation model. However, in general, the first symptom that describes a divergence between the plant and the model occurs at the failed transmitter. Therefore, the strategy that is employed by APACS is to immediately generate hypotheses corresponding to a transmitter failure upon the arrival

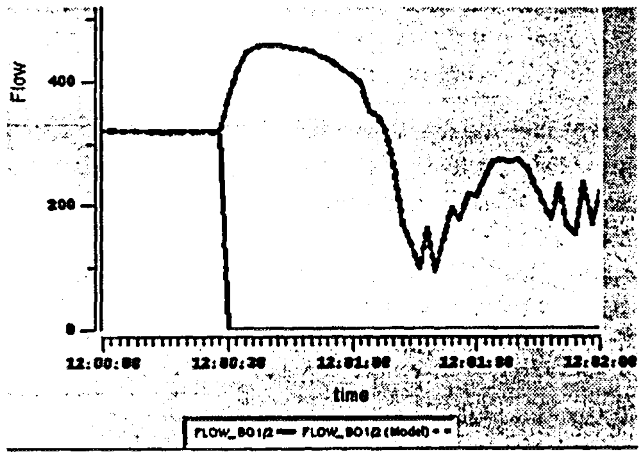

Figure 4: Deviation Between Model and Measured Reading For a Transmitter Failure

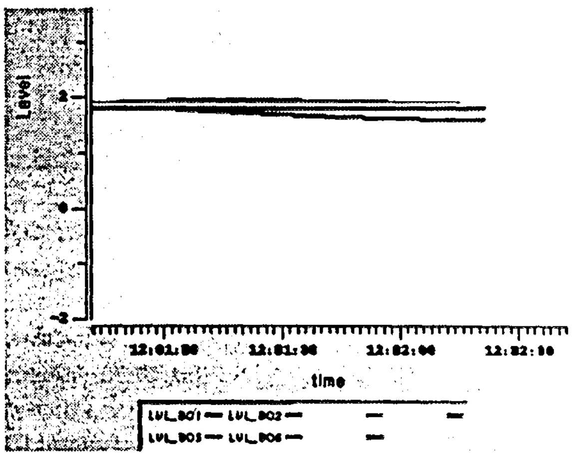

Figure 5: Boiler Levels in a Subtle Failure

of the first trigger associated with a transmitter. At the same time, *Diagnosis* continues to attempt to explain the symptoms in the usual way. If the problem is in fact a transmitter failure, *Verification* assigns a higher score to that hypothesis than any other failures that might be generated. Conversely, in cases where the problem is due to some other failure, the score for the correct hypothesis is higher. Figure 4 shows how the model (dashed) differs from the measured value for a particular transmitter as the transmitter fails suddenly to producing no value.

APACS models two kinds of failure at transmitters: *transmitter stuck* and *transmitter offset. Verification* models *transmitter stuck* by fixing the value of the transmitter at its value at the hypothesized time of the fault. If the transmitter is in fact stuck, there will be a minimal difference between this fixed value and the measured value over the time of the verification run, thus the hypothesis will have a high score. For *transmitter offset, Verification* assumes that the actual flow is fixed distance away from the measured flow.

4.2 Subtle Valve Failures and Valve Offsets

APACS is able to detect very subtle level control valve (LCV) failures including valve offsets. Figure 5 show a plot of boiler levels in a case where a particular valve sticks at close to its normal operating position. There is a slight change in boiler levels, but the plant's control computer is able to compensate for the failure and the boiler levels recover. It is quite possible that an operator would not be looking at these particular trends at the time of such a failure and would miss its occurrence. APACS' monitoring component, on the other hand, detects the deviations of the boiler levels from their set points and the fact that the flow at a sensor upstream from the particular boilers deviates slightly from the model. This results in several events that diagnosis explains by a failure that allows extra flow through a particular valve (that is, the valve opens slightly.) For this kind of failure, Diagnosis requests that Verification check both the possibility that the valve is stuck at some position and that the valve is consistently offset from its demanded position. As mentioned above, the possibility that the flow transmitter has failed is also hypothesized. Figure 6 shows a summary of the verification results as accumulated by Diagnosis where the valve stuck hypothesis (LCV16_TROUBLE) has a higher score than the valve offset hypothesis. The correct result was reported within two minutes of the time of the failure.

```
@Transmitting result at 146.208                                         Score
@Request Summary 04/05/96 07:56:03 lcv16-600-i
@     Request0          FT8_OFFSET [120054,120102][ 1.05, 1.25] 79.66 120104  1.05
@     Request1          NO_FAILURE [120054,120102][    0,    0] 82.59 120054     0
@     Request2           FT8_STUCK [120054,120102][    0,    0] 88.19 120102    22
@     Request3       LCV16_TROUBLE [120022,120038][0.396,    1] 95.81 120040 0.6137 ***
@     Request4        LCV16_OFFSET [120022,120038][ 1.05, 1.25] 93.15 120040  1.21
@     Request5       MV188_TROUBLE [120022,120038][    0,    1] 87.96 120022     1
@DIAGNOSIS: BO6 flow path stuck open (LCV16 to 61% at 120040)
```

Figure 6: Summary of Verification Results

4.2 Failures Outside of the Feedwater System

It is important that a system such as APACS not incorrectly report failures. In particular, if a failure occurs outside of APACS' domain of expertise, APACS must not report that a failure has occurred within its domain. For example, in the case of the feedwater system, failures in other systems such as the steam lines or the primary heat transport systems will often result in deviations between the feedwater model and the plant.

In many such cases, the diagnosis component will be unable to put together a consistent causal explanation of the symptoms and will report this fact to the operator. Frequently, however, the symptoms will result in hypotheses. APACS' strategy for dealing with this is to always generate a "no failure" hypothesis for verification in which the plant history is compared to a model of the feedwater system which assumes that it (the feedwater system) is behaving normally. If the "no failure" hypothesis has the best score, APACS informs the operator that the cause of the symptoms is most likely outside of the feedwater system. This strategy works quite well in the cases accumulated to date.

4.3 Sequential Multiple Failures

APACS is designed to be able to diagnose multiple failures that occur in sequence. Once *Diagnosis* has determined the best hypothesis with a time and severity as computed by the verification algorithm, *Diagnosis* instructs the APACS components to modify their models to take into account these faults. Since there is inevitable some error in the time and severity of the fault, *Monitoring* must use a set of widened thresholds. While this work is just beginning, APACS has successfully diagnosed both failures in such sequences. The scenarios that have been used consist of valve failures of various magnitudes that are insufficiently large to cause a plant trip, followed about 4.5 minutes later by a second failure. Since APACS is unable to supply a reference model (UAM) for the plant until *Diagnosis* and *Verification* have determined the nature of the first fault, there is a window in which a second fault can never be detected. This window currently averages about two minutes on a recent model Risc workstation; the size of the window is to a large extent due to the fact that *Verification* needs to collect about a minute's worth of data following the time of the fault in order to discriminate between hypotheses.

5.0 Related Work

Knowledge-based diagnosis, especially of continuous processes, is a difficult problem and an area of active research [18]. Early attempts at diagnosis consisted of rule-based systems such as MYCIN [16] but have been found inadequate since they are brittle, difficult to maintain, and too closely tied to a particular application. More recently, research in diagnosis has focused on model-based techniques ([2], [15], [4], [13]). In a model-based diagnosis, a diagnostic inference engine uses a knowledge-based model of the domain in order to find the cause of the problem. The model is generally a qualitative description [3] of the behaviour of the artifact being diagnosed. Model-based approaches have typically been applied to systems such as digital circuits in which it makes sense to use a model consisting of equations describing equilibrium conditions. Attempts to apply the model-based approach to continuous processes include [5] and [12] in which the model of the domain consists of a qualitative simulation. The APACS framework is a unique approach to model-based diagnosis in that it uses the quantitative (numerical) simulations in the plant analyzer components to generate discrepancies and test candidate hypotheses. A major advantage of the model-based approach is that it avoids the proliferation of rules linking symptoms to faults that is a prominent feature of rule-based systems; APACS has less than 100 rules.

Other approaches to developing systems and frameworks for continuous processes include ARTIST [17], IOMCS [14], CA-EN [1], and REAKT [6]. These systems, while they share the goals of APACS, generally have been applied to small problems, lack the high-fidelity real-time numerical simulations and tracking algorithms, and except for IOMCS, do not provide an architecture in which separate processes share a common view of the problem and the domain.

Another related project is ARCHON [7] which is an architecture for connecting many communicating processes and which has been applied in the process control domain. ARCHON is an agent architecture in which process have considerable knowledge about their own capabilities as well as the capabilities of other agents with which they must deal. For APACS, in contrast, the much simpler protocol in which processes make requests for certain classes of objects without knowledge of the supplier has been perfectly adequate.

6.0 Conclusions

In summary, the APACS project has developed a technology for monitoring and diagnosing industrial processes and has demonstrated, in a particular application, that successfully diagnoses several interesting classes of failures. Particularly noteworthy is the fact that multiple serial faults, transmitter failures, and very subtle failures have been successfully diagnosed. Key reasons for this success include the use of a numerical simulation as a reference model for detecting subtle excursions in plant behaviour and distinguishing between hypotheses, and the use of a parameter adjustment algorithm for matching the reference model to the plant over longer periods of time. The model-based approach allows APACS to do the job with relatively few rules.

Although APACS has to date been tested on a single application, the technology is generic due to the openness and portability of the overall APACS architecture and by its ability to support the definition of data communication protocols among components independently of the individual APACS components. The use of a centralized knowledge base to isolate the domain specific knowledge should reduce the overhead involved in building new APACS systems for similar situations.

While the APACS project officially ended on March 31, 1996, a follow on pilot application project has been initiated. For this effort, the prototype has been connected to the training simulator at Ontario Hydro's Western Nuclear Training Centre where station operators and technical unit staff are being asked for feedback into the design and performance of the system. At the same time, work has been started to connect APACS to a running unit in the Bruce B station. A pilot trial of a full scale APACS attached to this unit is planned for later in 1996.

ACKNOWLEDGMENTS

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DETECTION OF LEAKS IN STEAM LINES BY DISTRIBUTED FIBRE-OPTIC TEMPERATURE SENSING (DTS)

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ABSTRACT

This paper describes an instrumentation system concept which should be capable of early detection of a leak-before-break in main steam lines.

Distributed fibre-optic Temperature Sensing (DTS) systems have been used in commercial application for a few years now, but in other industries and applications. DTS uses very long fibre optical cable both as a temperature sensor and as a means of bringing the information back from the sensor to the terminal equipment. The entire length of the fibre is sensitive to temperature and each resolvable section of fibre is equivalent to a point sensor.

A typical application comprises 4km of fibre optical cable, in which the average temperature of every metre is measured as a temperature "point" to an accuracy of one degree C in a measurement time of 20 seconds. The fibre optic cable is measured at both ends, so that signals are not interrupted if there is a break in the cable. Breaks in the cable would be alarmed to the operator.

This commercially available DTS system could be adapted to indicate leaks in steam lines. The fibre-optic cable could either be run either just underneath the aluminium sheathing covering the insulation over a steam line, or between the two layers of insulation. This would detect an increase in the temperature of the insulation due to a steam leak.

For example, a fibre optic cable could be wound around a steam line with the cable turns spaced at 0.25m. For a steam line of 2.5 metre in circumference, there would be 10 temperature "points" per metre of pipe which should provide adequate coverage for detecting a local increase in temperature of the insulation due to a steam leak.

In the above arrangement, a 4km fibre optic cable could monitor a total length of 300 metres of steam lines, allowing 100m for connections back to the DTS terminal equipment.

Because the temperature of the insulation is not very high, a commercial grade plastic covered fibre optic cable might be suitable, although cables in flexible stainless steel tubing are also available.

A test rig is being set up in Canada to test the above concept, and to determine the minimum spacing required between the turns of fibre optic cable required to achieve an adequate response time.

1. REQUIREMENT

It has become a requirement in the design and operation of nuclear power stations to consider the possibility of a guillotine failure of a main steam line and the effect of consequent pipe whip, pressure surge or the effects of steam on safety related equipment, the main control room and operators. In some stations, blow out panels have been added to the turbine building and adjacent rooms containing safety related equipment have had walls and doors strengthen. In the design of new stations, these requirements can be largely accommodated in an improved layout where interlocked steam proof double doors will prevent steam getting into safety related equipment and areas.

However there is the argument that a guillotine failure of a well designed steam line would be proceeded by a leak-before-break. Such steam leaks could be detected by very frequent visual inspection but this may be difficult because of the length and location of the steam lines. Therefore a practical, reliable and easy to interpret instrumentation system to detect such steam leaks has been sought.

2. TECHNICAL CONCEPT

Distributed fibre-optic Temperature Sensing (DTS) systems have been used in commercial application for a few years now, but mostly in other industries and applications [1].

In the DTS system, a single optical fibre is used both as a temperature sensor and as a means of bringing the information back from the sensor to the terminal equipment. The entire length of the fibre is sensitive to temperature and each resolvable section of fibre (typically 1m long) is equivalent to a point sensor. A laser signal is sent into one end. Reflections occur all along the cable and are returned to the sending end where these reflected signals are measured. The distance along the cable of these reflections is detected, and the return signal from each point is proportional to the temperature at that distant point.

The terminal equipment which comprises an Opto-electronic unit with built in data processing with out put to a PC video display.

It is not the purpose of this paper to describe this DTS technology; details may be obtained from the inventors and suppliers of the equipment, but rather to describe a concept for the application of a DTS system to detect leaks in main steam lines.

3. RECENT APPLICATION OF DTS.

A recent application of DTS has 4km of optical fibre providing 3000 temperature points measured every two minutes, with only four fibres back to a single scanning system. Reference [1], (page 116 (a) Process plant through to top of page 118), describes a DTS installation monitoring the condition of pipework associated with the filtering in a pressurised fluidised bed combustion (PFBC) power generating plant in Japan.

By coincidence, four steam lines are a common arrangement at a nuclear power station, so the DTS installation at this PFBC power station is a useful reference design.

3. APPLICATION NUCLEAR POWER STATION STEAM LINES

3.1 Steam Line Leak Detection

If conventional point temperature measurements are used, subjective decisions have to be made about where steam leaks are most likely to occur, because it would be practical to only install a few individual temperature points because of the large quantity of separate wiring per point that would be required.

The advantage of the DTS system is that very comprehensive temperature measurement coverage can be provided over the whole length of the steam lines in a practical and relatively economic way so that no subjective decisions have to be made as to where a leak might be likely to occur due to internal erosion of the pipe. Also leakage of steam lines caused by other low probable external events would also be covered.

In considering the possible application of DTS for leak detection on the steam lines of a nuclear power station, the following points are relevant;

3.2 Temperature Resolution v Time

There is a trade off between measurement time, temperature resolution and length (range) of the fibre-optic cable. The above PFBC application of 4km sensor cable, has a temperature resolution of 0.5 deg. C; hence the relatively long scanning time of 2 mins.

However a resolution of 1 deg. C can be achieved in a measurement time of 20 seconds, and 5 deg. C in 5 seconds. One of these may be a more appropriate specification for nuclear steam lines where speed of alarm response to a high temperature differential may be desirable.

3.2 Double Ended Sensor Configuration

The fibre optic sensor cable can be measured at both ends which provides the following advantages in a safety critical application;

- signals are not interrupted if there is a break in the cable.

- break in the cable would be alarmed to the operator.

- dynamic loss variations along the sensor fibre elements are compensated, thus optimising signal-to-noise performance.

3.2 Fibre Optic Cable Specification

The fibre optic cable requires is Standard Communications Grade G1 multimode optical fibre, but there is a choice of both the fibre optic sensor element and the secondary sheathing depending on the temperature rating required and the physical protection desired.

For example, a polimide primary mechanical coating has a temperature rating up to 385°C.

The secondary sheathing of plastic might be appropriate for this application, but stainless steel would be better. The cable would have an overall diameter of about 2mm.

3.3 Coverage Possible

The approach in developing the technical concept was to identify the maximum possible coverage that could be achieved by utilising the 4km length of sensor cable in four loups, as used in the PCFB example.

The initial concept was for the fibre optic sensor cable to be run as a spiral "Bobbin" winding pattern around a main steam line which has an overall external circumference of about 2.5 metres. This would provide 10 temperature "points" per metre of pipe length. This should be the maximum coverage of temperature points that could possibly be required to detect an increase in local temperature due to a postulated steam leak. This spacing may be much smaller than really required.

In the above arrangement, 4 km of fibre optic cable could monitor a total of 300 metres of steam lines, allowing 100m of cable for connections back to the DTS equipment in the main control room. The longest steam line was assumed to be 100m.

Each of the four steam lines would have a separate double ended loop connected to the DTS terminal equipment, similar to the connections and data processing of the PFBC reference design.

3.4 Average temperature

The DTS system can calculate various reference temperatures;

- An average temperature for the sensor cable along the whole length of a steam line.
- The external ambient temperature.
- Absolute temperatures of each "point"

Temperature increase of any "point" above a margin set on the reference temperature(s), would be is alarmed.

4. INSTALLATION OF THE FIBRE OPTIC CABLE.

4.1 Practical problem of cable installation.

The application of the "bobbin" pattern would require winding one km of sensor cable around a 100m long steam which would present the following practical problems;

- the steam line has many bends, supports, restraints ("snubbers"), and flow measuring tubing connections, which would have to be circumvented.

- After a few turns, the fibre optic cable would be very difficult to feed out and could get in a knot.

- Many splices in the cable would be required as obstructions are passed and the cable is tightened.

- If during subsequent service, repairs to the insulation or inspection of the actual pipe was required, the fibre optic cable would be to be broken and reconnected. Such reconnections are possible and would only result in a small loss of signal, but it would be desirable to minimise such joints.

It became obvious that "bobbin" winding pattern would be unpractical, so the following alternative cable patterns were considered.

4.2 The "Straight" run of cable.

In the "Straight" option, 10 parallel sensor cable runs would be required to give the same coverage as the "Bobbin" pattern used in the above calculations providing the "maximum possible" coverage.

It may be that this "maximum possible" coverage is not required, and that two parallel cables would suffice; one cable along the top of the steam line (at 12 o'clock) and one along the bottom (at 6 o'clock) with perhaps supplementary runs on each side (at 3 o'clock and 9 o'clock).

The disadvantages of this sensor cable pattern are;

- On a steam leak, alarms would be generated by more than one of the "straight" cables. This would not matter in the case of a major leak, when the operator action would be to shutdown the plant, but might cause confusion in the case of a small leak.

- It is a requirement that a cable pattern should appropriate for either a horizontal or vertical length of steam line, both in terms of installing the cable and in terms of the flow of steam from the leak through the insulation. It is not clear how the "straight" pattern would meet the latter requirement.

- This pattern does not take full advantage of the coverage capabilities offered by a DTS system.

- There are the other disadvantages similar to the "bobbin" method.

4.3 The " U-Turn" winding.

A simple small scale model of a steam line was made to try out alternative cable installation patterns.
The "U-Turn" or "serpentine" pattern was conceived, as shown in the attached Figures 1, 2, 3 and 4.

This pattern turns out to have some interesting advantages as described in the figures, and makes the installation more practical. The coverage of the cable would be adequate for both a horizontal or vertical steam lines.

5. LOCATION OF THE SENSOR CABLE.

5.1 Steam line Cross section

A typical steam line cross section comprises, described from inside to outside;

- The steam pipe
- Two 2"(5mm) thick layers of hard Calcium-Silicate insulation.
- An aluminium sheathing.

There are three possible optional locations for installing the fibre optic cable;

5.2 Outside of the aluminium sheathing.

It may seem easier to install the sensor cable outside the aluminium covering, but has this location has the following disadvantages;

- The sensor cable would be sensitive to external temperature, such as the sun. It is possible to compensate for these external effects by data processing. For example, one circumference of sensor is about 2.5m and could be considered as four overlapping one metre temperature "points". The temperature readings of all the points having the same orientation could be averaged along the whole length of the steam line, and increases above this average alarmed.

- The sensor cable would have to be affixed to the aluminium with a temperature conducting paste.

- Damage to the cable; a stainless steel sheathing would offer some protection.

5.3 Between the aluminium sheathing and the top layer of insulation.

It is fairly easy to install the cable between the aluminium sheathing and the insulation, because the insulation is removable in convenient sections. The aluminium would prove some shielding from external temperature effects and would provide good physical protection.

5.4 Between the two layers of insulation.

Locating the sensor cable between the two layers of insulation would be ideal from considerations of shielding from thermal effects, but on an existing plant, requires the removal of one layer of insulation.

6. TEST RIG

It may be that a sensor cable in any of the above alternative locations would give a satisfactory indication of steam leak which should cause a significant increase in the local temperature of the insulation well above the average temperature as measured along the total length of the sensor cable for the individual steam line.

It is planned to determine the optimum location of the sensor cable and to demonstrate the performance of the DTS system on a test rig in Canada. This test is already partially erected and comprises a 3 metre length of full size steam line with the same cross section as described above. This test line has been arranged to simulate a variety of different sizes of steam leaks.

The sensor cable will be installed in the three locations described above and in both the "U-turn" and four "straight" patterns.

Tests will determine the comparative response of the various locations, patterns and the spacing required between the turns of the sensor cable to obtain the desired indication of a specified steam leak. Results should be known before the end of this year.

7.CONCLUSIONS

The inventor and supplier of the DTS system has stated that there are 82 DTS units in service in different countries in a wide variety of applications, with an average mean time between failures of 6 years.

One DTS unit has been in satisfactory service in Canada for a few years on an electrical power application.

Tests have already been successfully carried out on test length of steam line at a coal fired power station in the UK, but using a "straight" pattern of sensor cabling.

The author has witness demonstration tests of the response of the DTS system to heat applied to a one metre length of one km coil of sensor cable. The distributed temperature sensing technology appears to be reliable commercial product.

The application of DTS to the detection of leaks in steam lines seems to be a matter of specific application design, selecting a practical pattern and acceptable depth of location of the sensor cable installation, and the desired processing of the temperature data and presentation to the operator.

Temperature is a well understood phenomenon and should be easy to interpret by the operator.

The tests planned to be carried out in Canada in the near future should indicate the optimum application design.

ATTACHMENTS

Figures 1,2,3 and 4 of the "U-turn" sensor cable pattern

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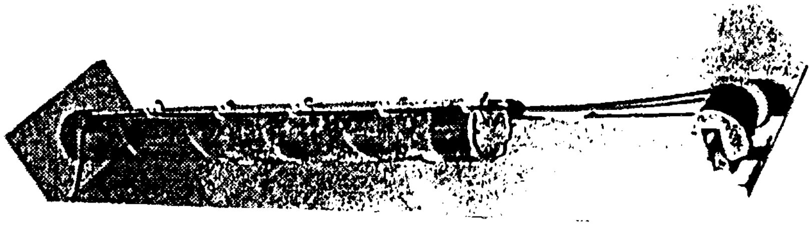


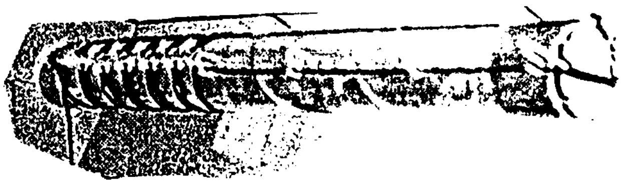
The start.

An initial length of cable has been drawn off the cable drum at one end of a section of steam line, and pulled along through by 5 pulleys (white), to the other end of the steam line.

A few turns on.

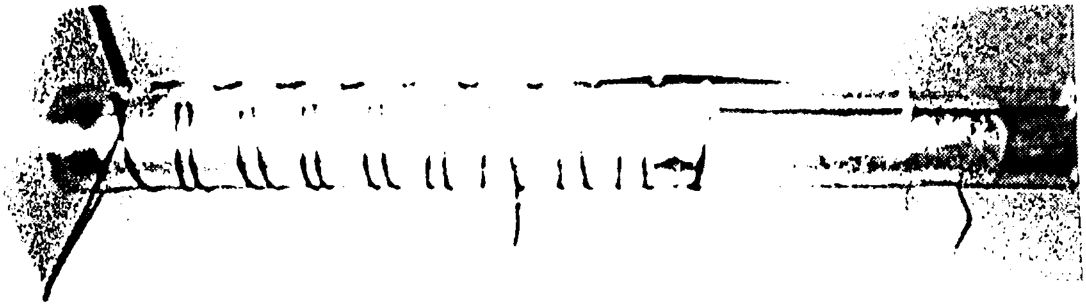
Cable has been drawn off the cable drum as required.

The "U-Turn" fixings (yellow) at the top of the steam line are shown.



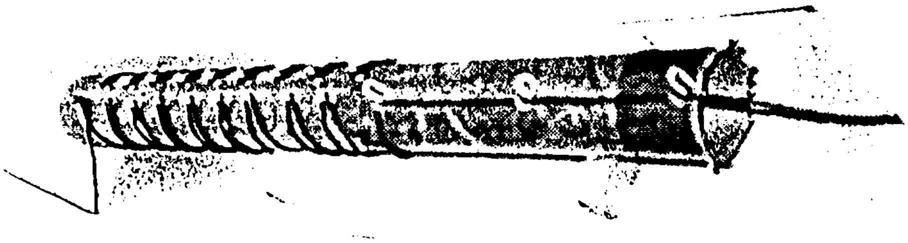
FIBRE-OPTIC CABLE "U-TURN" PATTERN
INSTALLATION PROCEDURE

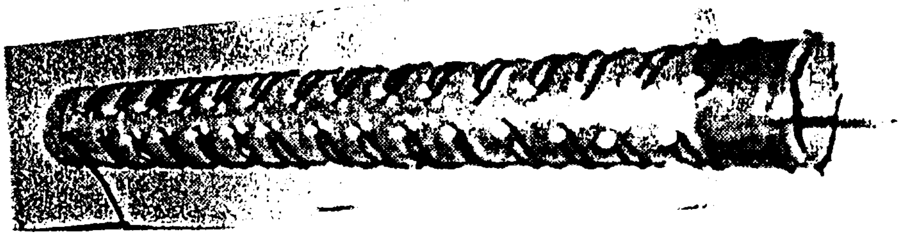
Fig. 1



Half way;

This shows how the cable passes an a typical obstruction
such as a pipe support.

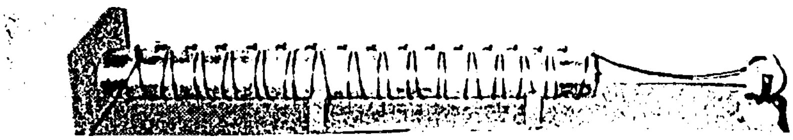




Cable installation complete.

The "U-Turn" support fixings are shown farther apart for clarity.

This shows how the cable passes typical obstructions;
two pipe supports.



FIBRE-OPTIC CABLE "U-TURN" PATTERN
INSTALLATION PROCEDURE

Fig. 2

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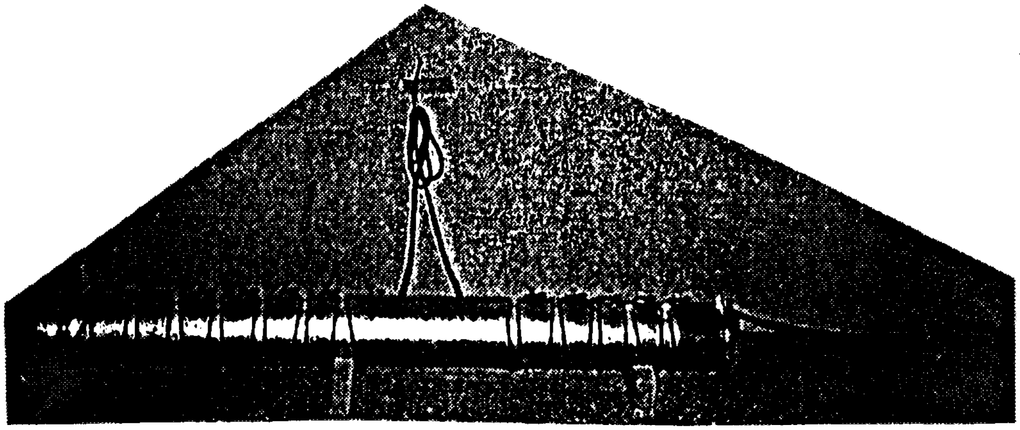
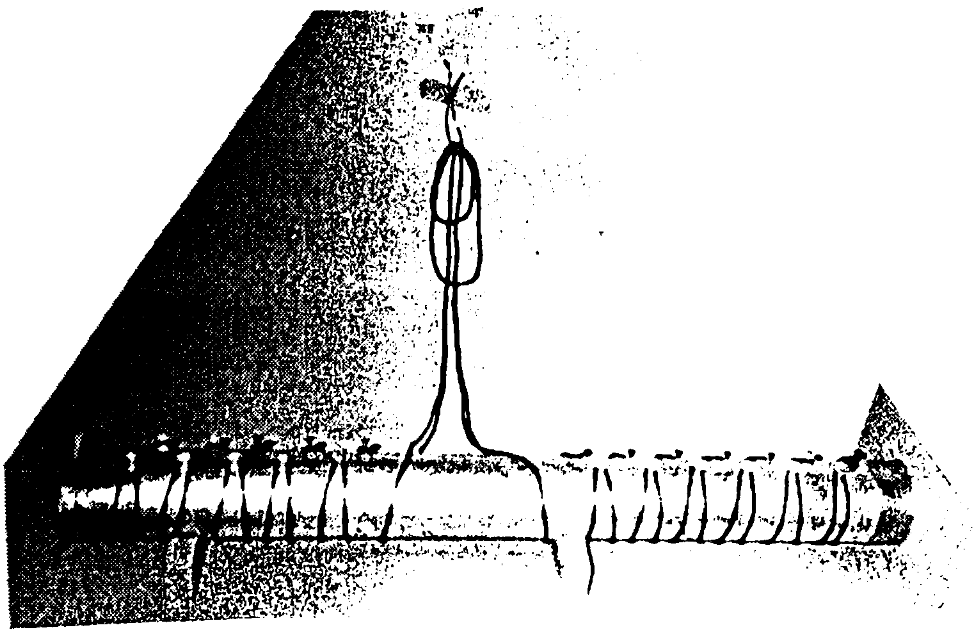


Access for repairs/inspection of the insulation or the pipe; cable removed over.



Access for repairs/inspection of the insulation or the pipe; cable removed under.

The cable is pealed away from the steam line without cutting the cable or requiring splice joints on reassembly.

(The apparent double cable is a shadow)

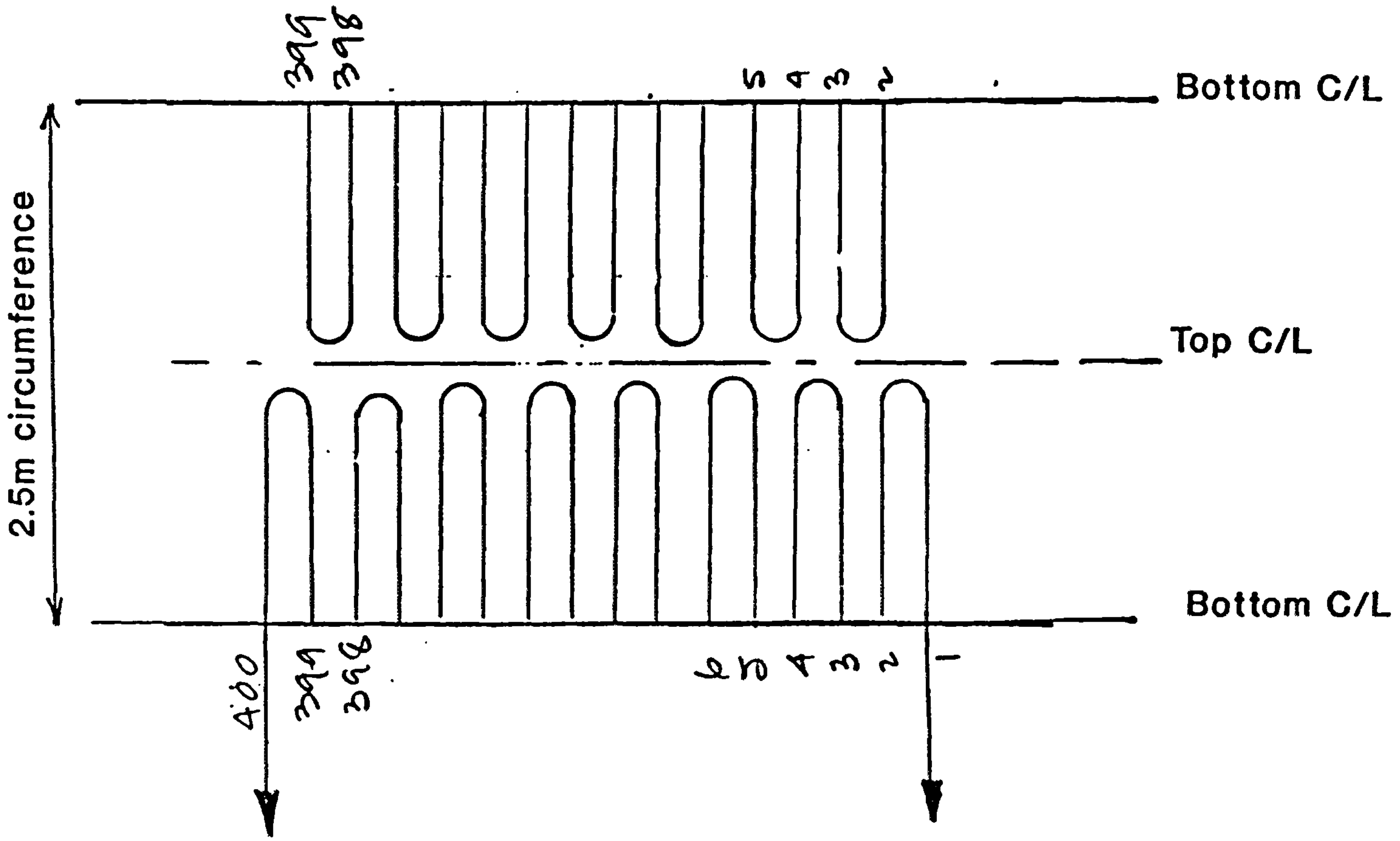
FIBRE-OPTIC CABLE "U-TURN" PATTERN
INSTALLATION PROCEDURE

Fig. 3

"U-turn" sensor cable pattern

Steam line, 100m - developed view

Sensor spacing - 0.25m



To/from Opto-electronic unit

Fig. 4 - "U-turn" senor cable pattern

XA9743560

LEAK DETECTION SYSTEM FOR RBMK COOLANT CIRCUIT

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ABSTRACT

In report the description of an object of the control is submitted, requests to control of leak-tightness and functioning of system are formulated, analysis of an current status on NPP with RBMK is submitted, review of methods of the leak-tightness monitoring, their advantage and defects with reference to conditions and features of a design RBMK is indicated, some results of tests and operation of various monitoring methods are submitted, requests on interaction of operative staff, leak-tightness monitoring system and protection system of reactor are submitted.

1. INTRODUCTION

Now in Russian Federation there are in operation 11 units with RBMK reactors on 3 NPP (Leningrad NPP, Smolensk NPP, Kursk NPP). 2 units with RBMK are maintained on Ignalina NPP, Lithuania and 3 units with RBMK - on Chernobyl NPP Ukraine. After failure on Chernobyl NPP in reactor design significant changes were introduced. Besides the organizational and design decisions with purpose decrease of probability of heavy failures was carried out. On each unit stage by stage occurs reconstruction of the process equipment and equipment by additional systems of safety. One of important steps for increase of safety of operation NPP with RBMK is implemetation of the leak detection system for reactor coolant circuit.

The leak detection system for RBMK coolant circuit is intended for decrease of probability of emergencies, connected to break of pipelines and component of a reactor coolant circuit, and also decrease of an exit of radioactive elements for limits of the sanitary norms.

The necessity of the leak- tightness monitoring for reactors coolant circuit is confirmed by requests of Russian regulating bodies and for NPP with RBMK is a urgent problem.

2. DESCRIPTION OF THE RBMK COOLANT CIRCUIT

The multiple forced circulation circuit(MFCC) is one of main systems of the RBMK and is intended for:

- maintenance of continuous circulation of the heat-carrier through reactor core with the purpose of removal of heat from a fuel assemblies and graphite blocks of reactor;
- separation of generated in reactor a steam with subsequent submission him in turbine branch;
- maintenance of necessary conditions for reactor heating and reactor coolant;
- cooling of an reactor core in modes scheduled or emergency coolant of the unit at the expense of compulsory and natural circulation of the heat-carrier;
- removal a residual heat release from reactor during long shut down of the reactor unit.

Submission of water (underheating before boiling) to each channel is carried out individually from below on pipelines of the water communications. The water, washing fuel elements, in core is heated up before boiling and partially turns in pairs. Steam/water the mix from top part of channels on individual pipelines steam/water of the communications concerns in steam-separators.
On fig. 1 the basic scheme of a RBMK - 1000 circuit is submitted.

The circuit consists of two parallel loops, the equipment of which Is located symmetric concerning vertical axial plane reactor. In each loop there is on 2 steam-separators(SS), intended for allocation from steam/water mix dry saturated the steam. БC represents a horizontal cylindrical vessel. Inside case a steam are located equipment, intended for steam separation.

SS on each half MFCC are connected two cofferdam on water and five cofferdam on steam.

Inside each separators along bottom forming a collector of nutritious water is located. From this collector through special branch pipes - amalgamators the nutritious water moves in 12 downcomers each separators. The water, being mixed with nutritious water, on 24 downcomers arrives in suction header of main circulation pumps(MCP), from which on suction pipelines, the water arrives to 4 MCP. Normally in each loop works on 3 MCP and on one is in reserve.

From MCP on pressure head pipelines the water arrives in pressure header. On pressure head pipelines each MCP are consistently established the return valve. A suction header and pressure header of each loop are connected a branch headers. Branch headers have normally open valve and return valve. Through branch headers natural circulation of the heat-carrier is provided at emergency switching-off MCP. From pressure header on 22 pressure pipelines the water moves in 22 distribution group header.

From distribution group headers the water moves in pipelines of the water communications. To each distribution group headers is connected 40-43 pipelines of the water communications.

Thus, each loop MFCC cooling of a half of fuel channels reactor is carried out. The direct connection between halves of a circuit on water is away.

Steams from each SS is removed on fourteen pipelines in two steam collectors, which then are united in one pipeline. Further of steams on four steam pipelines is directed to turbines and to other systems.

Fulfilling of steams is condensed, is cleared, is warmed up, is mixed with planimetric water, past clearing, and moves in drum separators

The pipelines and equipment MFCC are located in isolated premises. The circuit of an arrangement of the equipment is indicated on fig. 2.

3. CURRENT SITUATION ON NPP WITH RBMK

From the point of view of leak-tightness monitoring the coolant circuit of reactor conditionally can be divided into two parts: fuel channels and other part of a contour.

Each unit RBMK has the monitoring system of integrity of fuel and special channels (IFSC), stipulated by the design decision NPP. The IFSC system is a component of system of the technological control reactor and technological ventilation system of a gas reactor circuit. The scheme of IFSC system is submitted on fig. 3,4.

The IFSC system is intended for:

- group humidity monitoring of gas, from graphite blocks;
- definition damaged fuel channels;
- uniting of a moisture from damaged channel in adjacent cells.

The work of IFSC system is based on measurement of parameters of gas (temperature, humidity) at distribution him from below upwards on gas pathes of channels through graphite blocks and pulsing pipelines. Temperature of gas is measured in each of 2044 channels.

The relative humidity of gas is supervised in 26 zones on 81 channels each.

The operation of IFSC system on units with RBMK-1000 has demonstrated her serviceability at definition damaged of the channel. However at small leaks in region of the bottom adapter of the fuel channel there were the cases of ambiguous definition of the defective channel. It expressed that at one damaged channel temperature was increased simultaneously in several pulsing lines, owing to distribution a steam through graphite blocks.

For removal of indicated defect additional bottom IFSC system was introduced. A principle of work bottom IFSC similar IFSC. The gas mix from bottom part of reactor space branches on two flows, one flow on gas pathes of channels arrives to pulsing lines IFSC, other through bottom pathes and drainage pipelines of channels of a protection system in bottom IFSC. The measurement of temperature is made on drainage pipelines of each channel of a protection system. Appearing in reactor space the moisture evaporates and, partially being condensed at contact with surface of "cold" channels of a protection system, is merged in a cavity and further gets in drainage pipeline. Thus, temperature of the drainage pipeline becomes lower than temperature of air in premise of the bottom water communications, that is fixed thermoelectric transducers.

For other part of a coolant circuit by the design decision NPP with RBMK is not stipulated of the specialized leak-tightness monitoring system . Now, basically, the leak-tightness monitoring of pipelines and component of a coolant circuit is carried out by analysis of activity of air environment in circuit premises. The analysis of activity is carried out by continuous control of activity of radiogases and radioparticulate regular system of radiating safety and laboratory analysis. Besides on each unit with RBMK there is the reactor protection system on increase of pressure in premises MFCC.

4. REQUEST TO LEAK-TIGHTNESS MONITORING

The RBMK coolant circuit, except for fuel channels, includes in self the following equipment and pipelines:

- steam separators - 4 items;
- separator's steam branches - 10 items;
- separator's water branches - 4 items;
- downcomers - 48 items:
- suction headers - 2 items;
- large diameter suction pipelines - 8 items;
- large diameter pressure pipelines - 8 items:
- pressure headers- 2 items;
- distribution group header - 44 items;
- water communication lines - 1693 items;
- steam-water communication lines - 1693 items.

The leak-tightness monitoring of this part of a RBMK coolant circuit should be carried out with fulfilment of the following requests:

a) the system of leakage detection should provide the possibility of detecting small leakages at a very early stage of its origin and provide preventive alarm to the unit control room;
b) in case the size of the detected leakage is equal to 3.8 l/min and it is identified, the system shall provide preventive and alarm signals to the unit control room;
c) the period of time necessary for the detection of the leakage equal to 3.8 l/min as well as for its identification and alarm signal output shall not exceed 1 hour;
d) leakage detection shall be carried out by 3 independent physical parameters;
e) requirements indicated as b) and c) shall be met for each of 3 monitored parameters;
f) the system shall determine the leakage location.
The detection accuracy of the leakage location at the controlled equipment and pipelines, shall be :
- for equipment and pipelines with diameter > 300mm - up to 1m
- for pipelines of steam/water communication lines and lower water communication lines with the accurate location up to the specific pipeline.
g) In case of coolant leakage detection the coolant outflow shall be estimated.

5. MONITORING METHODS

The majority of methods of the control of tightness are described in standard IEC-1250. Each of described IEC of methods in various performance is applied to leak- tightness monitor on majority NPP.

The main comparative characteristics of methods are indicated in table 1.

However, applicability and the characteristics of methods in large degree are determined by design features of reactors. Variety of leak monitoring methods and the specific requests of plant to leak detection should be individually considered by the designer for determination of applicability of the leak-tightness monitoring system for each station.

5.1. Sump monitoring

Sump level and sump pump discharge flow monitoring leakage detection with reference to operating conditions and design features RBMK cannot have of sufficient sensitivity for detection small leak and can not to locate leak.

5.2. Air radioparticulate activity monitoring

Air radioparticulate activity monitoring is now applied on all units with RBMK to detection and valuation of leak outflow of the heat-carrier. This method have a follows attribute:

- high sensitivity of leak detection, high reliability of results detection;
- opportunity of leak rate valuation of the heat-carrier.

To defects of the given method concern:

- strong dependence of sensitivity on atmosphere mixing characteristics in controllable premises;
- dependence of results on changes of concentrations of detectable isotopes in heat-carrier;
- inability to locate leak;
- inability to distinguish multiple small leaks in various places of one premise from one greater size.

5.3. Air radiogas activity monitor

This method has attribute and defects, as a method air radioparticulate activity monitoring, But can be used only for monitoring of a limited part of a coolant circuit, which contains a steam phase. These steam/water pipelines, top parts of steam-separators and steam pipelines. This circumstance is caused by that the large part of gases together with ferry is directed on turbine and then on system of suppression of activity. Therefore, the concentration of gases in heat-carrier is very small.

5.4. Condensate flow monitoring

The efficiency of measurement the flow rate of the condensate for leak is unsufficient. Because, condensation of air environment in ventilation systems from premises of a coolant circuit RBMK occurs after assotiation of air flows from different premises. Moreover for some premises of a coolant circuit the results of the monitoring largely depend on amount of a steam phase of outflow.

5.5. Reactor coolant inventory

This method I cannot be used on RBMK with sufficient efficiency to detection small leaks.

5.6. Humidity monitoring

Humidity monitoring can be applied for leak detection in conditions RBMK, but has the following defects:

- strong dependence of sensitivity on characteristics of hashing of atmosphere in controllable premises and changes of humidity in normal conditions of operation;
- dependence of results on temperature of environment in premise and according to unknown proportion of water/steams at expiration of the heat-carrier for some premises of a circuit RBMK;
- inability to locate leak;
- inability to distinguish multiple small leaks in various places of one premise from one greater size.

5.7. Acoustic monitor

Acoustic monitoring using for analysis metal-borne acoustic wave of leakage and air-borne acoustic wave of leakage can be successfully applied for leak detection and leak location in conditions RBMK.. The attribute of a method concern:

- opportunity of leak location and accordingly ability to distinguish multiple small leaks in various places of the equipment from one greater size;
- fast leak detection and leak location.

To defects it is necessary to relate:

- strong dependence of sensitivity to leak detection from background noise magnitudes at each sensor location and the number of sensors.

5.8. Temperature monitoring

This method has good prospects for research of applicability on RBMK, but only in variant of remote measurement of temperature (thermovisual devices).

5.9. Pressure monitoring

This method cannot have of sufficient efficiency for small leak detection owing to long-duration period of time prior to the beginning changes pressure and low sensitivity for design decision NPP with RBMK.

5.10. Container moisture sensors

The application of this method for contour RBMK is complicated owing to large of a RBMK coolant circuit, and absence of thermal isolation on greater part of the equipment and pipelines. For some component of a coolant circuit this method may applicated. However the method has the following defects:

- at destruction of thermal isolation of pipelines, and as the consequence of the expiration of the heat-carrier in atmosphere, is possible reception of the false information about absence leak;
- difficulty of realization of resteam jobs at scheduled resteams.

The attribute of a method concern:

- opportunity of fast leak detection;
- opportunity of location leak;
- high sensitivity for small leaks.

5.11. Visual observation

The application of this method is inconvenient owing to high temperature of an environment in premises of a RBMK coolant circuit and difficult accommodation to existing design.
Thus, for satisfaction of stated above requests to leak-tightness monitoring for RBMK reactor the most expediently to use the following methods:

- acoustic monitoring;
- humidity monitoring of air environment in premises with equipment;
- radioactivity monitoring of air environment in premises with equipment.

6. TESTS RESULTS

For realization of the analysis of applicability and clarification of the characteristics of methods for leak detection on second unit LNPP a fragment of the leak detection system was mounted. The scheme of arrangement of acoustic sensor and sampling pipelines from controllable premise is indicated on fig. 5.

For realization of tests on reserve branch pipe of a distribution group header the stand leak-simulator was mounted. The drawing of the stand of the simulator is indicated on fig. 6. Remote control by the stand permitted to conduct tests of methods in real operating conditions at nominal parameters of the heat-carrier. The settlement size of outflow of the heat-carrier through stand - simulator at nominal parameters MFCC made 120 л/ч. Time of realization tests for various "opening" of the stand made from 3 up to 10 minutes.

During realization of tests in sampling pipelines was carried out suction of air from premise MFCC with cost 50 l/min in each pipeline. On fig. 7 dynamics of change of relative humidity in sampling pipelines during realization of tests is shown. The "Background" significance of relative humidity for all sampling pipelines did not exceed 20 % at the temperature of 25 C. This significance was constant from moment of start-up reactor and was not changed during year of operation.

At reduction of the stand of the simulator in "open" condition the relative humidity in near to stand pipelines (ТДК-85, ТДК-69) was increased more than 80-90 %. Transport time from moment of opening of the stand prior to the beginning increase of humidity made 1-2 minute. The humidity in distant from stand pipelines (ТДК-79, ТДК-91,043) was increased up to 50-60 %. The transport time made 3-5 minutes. After 5-15минут (for "near") and 30-120 minutes (for "distant") after closing of gates of the stand, the significances of relative humidity in sampling pipelines were reduced up to "background". Dynamics of change of humidity in pipelines sampling will be completely agreed geometrical arrangement sampling point, stand of the simulator and direction suction of ventilation in controllable premise and thermal flows inside controllable premise.

At valuation of applicability of an acoustic method of the control for leak detection of the heat-carrier the cross-correlation analysis of signals for steams of gauges was used. The availability of a maximum in normalized cross correlation function of signals from two gauges testifies to presence(finding) between them of a local source of noise. Coordinate on absciss axis corresponds to time of delay of a reception(party) of signals by gauges. Appropriate to a maximum of correlation function coordinate determines (at known wave speed) distance between source of a signal and site of the gauge.

The results of the correlation analysis for pressure tests of MFCC are indicated on fig. 8,9. The received times of delay of signals for all steams of gauges correspond(meet) to a real arrangement of gauges and place of leak-simulator. An error of determination of a site has made 0.3м. Cross correlation function are indicated in comparison with mode of nominal parameters of the heat-carrier. On fig. 10,11 spectrum of noise of the expiration for various gauges are indicated.

The experience of operation air radioparticulate/radiogas activity monitoring on NPP with RBMK has confirmed his efficiency for small leaks detection. By a while in service given method found out leak of the heat-carrier with cost less than 10 l/hour.

7. STATUS OF SYSTEM

The combination of functions of issue of an emergency signal for reactor shut down and informing of the operator on results of the control at early stage of occurrence of outflow of the heat-carrier, its(her) identification assumes organization of the control in kind of local automatic system, not claiming of interference of the operator in process of the control. Such system can execute protection reactor through operative staff according to rules on operation and duty regulations.

Leaktightness monitoring system shall provide the following functions execution when operating:

(a) transducers' signals acquisition, processing and analysis provided for each measurement channel;

(b) comparison of the measured and calculated values with predetermined limits;

(c) accumulation and storage of the current and previous values for each measurement channel in the information database;

(d) discovery of tendency of the recorded signals variation;

(e) sound and light warning and alarm of the "emergency" varying parameters;

(f) archiving the "emergency" situations ;

(g) coolant leakage size estimation;

(h) leakage position detection;

(i) self diagnostics of the components and elements.

Besides, the system shall permit the possibility of representation of graphic information concerning registered parameters variation, transducers interrogation, intermediate and emergency analysis results on the in-system display, under the condition there is no influence to all the functions. Leak-tightness monitoring system shall provide database and knowledge base creation and editing.

8. CONCLUSION

The results of tests and experience of operation of various methods, received in real operating conditions RBMK justify an opportunity of small leak detection of the heat-carrier from reactor coolant circuit. Satisfaction of requests to control of tightness and introduction of the monitoring system of tightness will allow to increase safety of operation NPP with RBMK reactors.

Table 1 - Summary of leakage monitoring instrument capabilities

Method	Leakage detection sensitivity	Leakage measurement accuracy	Leak location
Sump monitoring	A	A	C
Condensate flow monitors	A	B	C
Radiogas activity monitor	A	B	B
Radioparticulate activity monitor	B	B	B
Reactor coolant inventory	B	B	C
Humidity	A	C	B
Acoustic monitor	A	B	A
Temperature	A	C	B
Pressure	B	C	C
Tape moisture sensors	B	C	B
Liquid radiation monitor	A	B	B
Steam line radiation monitor (PWR)	A	C	A
Visual	B	C	B

NOTES

1. Capability ranking definitions are given below. This ranking is based on a consensus of operating experience with this instrumentation. Some instrument designs or plant configurations may justify a different ranking. The rankings listed above only provide guidance for leakage detection instrument selection.

A = Can generally be applied to meet the intent of this standard if property designed and utilized.
B = May be acceptable, marginal, or unable to meet the intent of this standard depending on application conditions and number of measurement locations.
C = Not normally recommended but might be used to monitor specific locations.

2. The use of some of these methods requires personnel with appropriate training or computerized information handling stems.

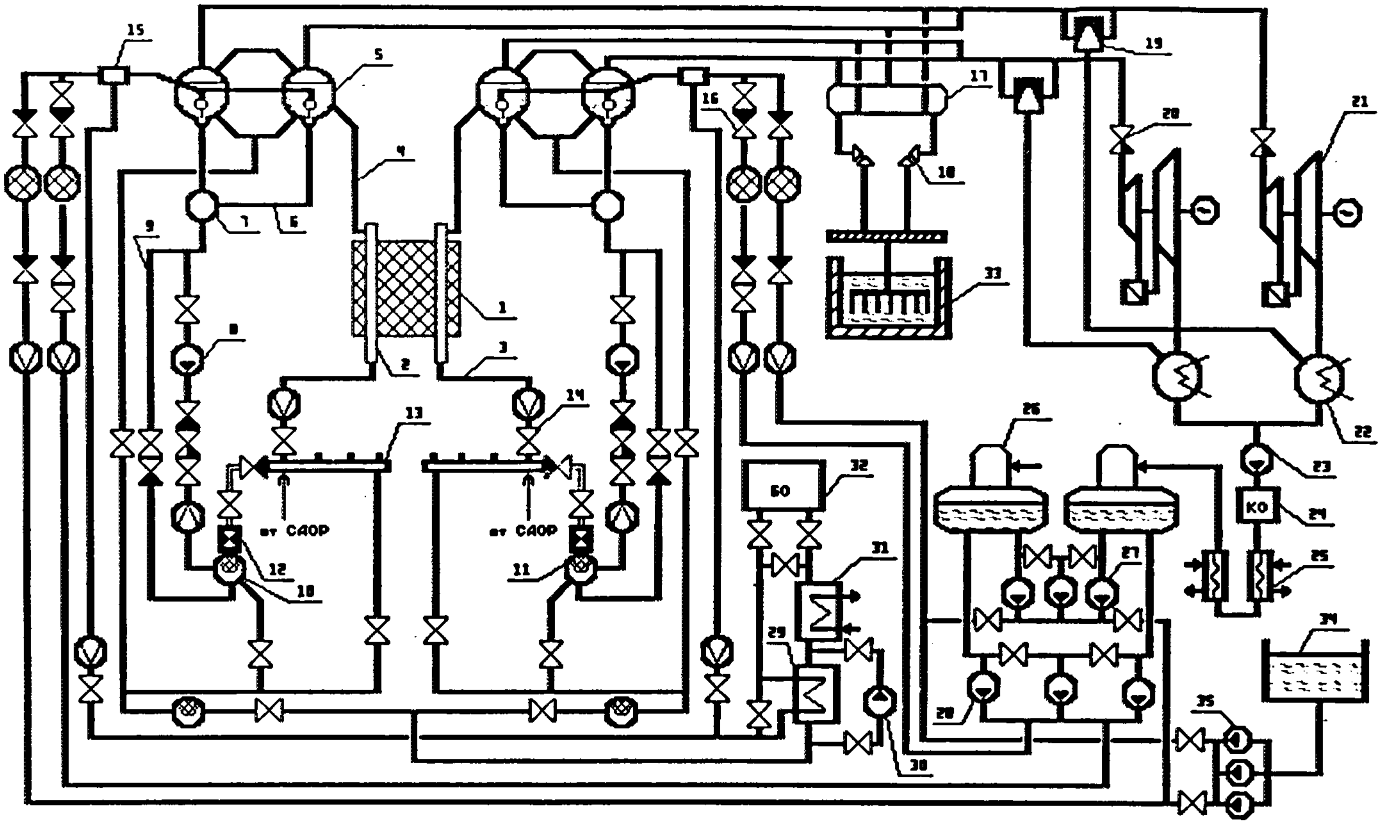


Fig.1 POWER UNIT PRINCIPLE LAY-OUT

1 - reactor; 2 - fuel channels; 3 - water pipeline; 4 - steam-water pipeline; 5 - drum-type steam separator; 6 - downcomers; 7 - suction header; 8 - main circulation pump; 10 - pressure header; 11 - filter; 13 - distribution group header; 14 - shutoff-and-regulation valve; 15 - mixer; 16 - feedwater unit; 17 - stream header; 18 - main safety valve; 21 - generator; 22 - condenser; 23 - condensate pump; 24 - condensate purification; 25 - low; 26 - deaerator; 27 - feedwater pump; 28 - small feedwater pump; 29 - regenerative heat exchanger; 30 - coolant pump; 31 - affercooler; 32 - bypass purification; 33 - condenser SLA; 34 - voluem water

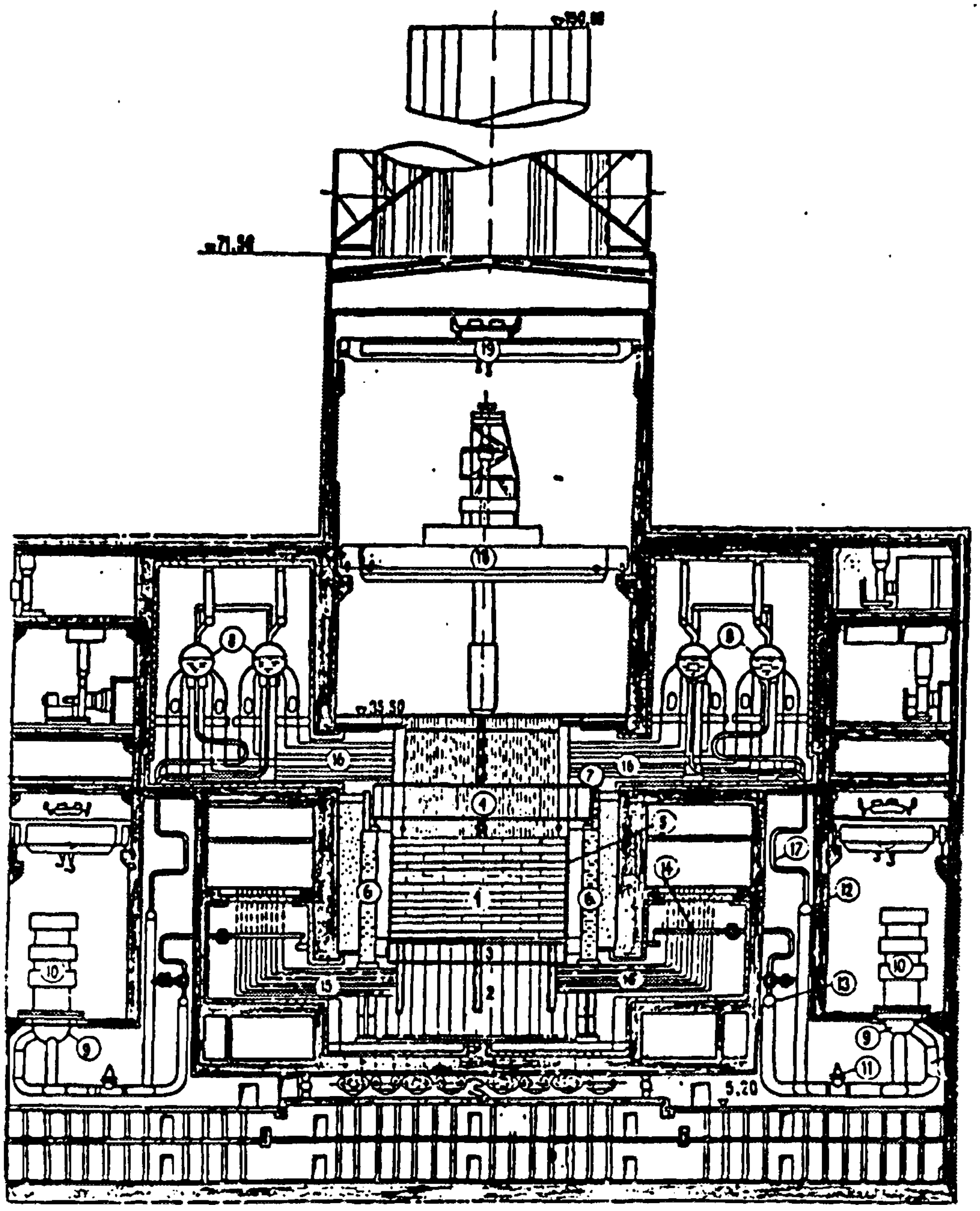


Fig .2 POWER UNIT SECTIONAL VIEW

1 - graphite structure; 2 - scheme "C"; 3 - scheme "OP"; 4 - scheme "E"; 5 - scheme "KG"; 6 - scheme "L"; 7 - scheme "D"; 8 - drum-type steam separator; 9,10,11 - main circulation pump; 12 - suction pipeline; 13 - pressure header; 14 - distribution group header; 15 - water pipeline; 16 - steam-water pipeline; 17 - downcomers; 18 - refueling machine;

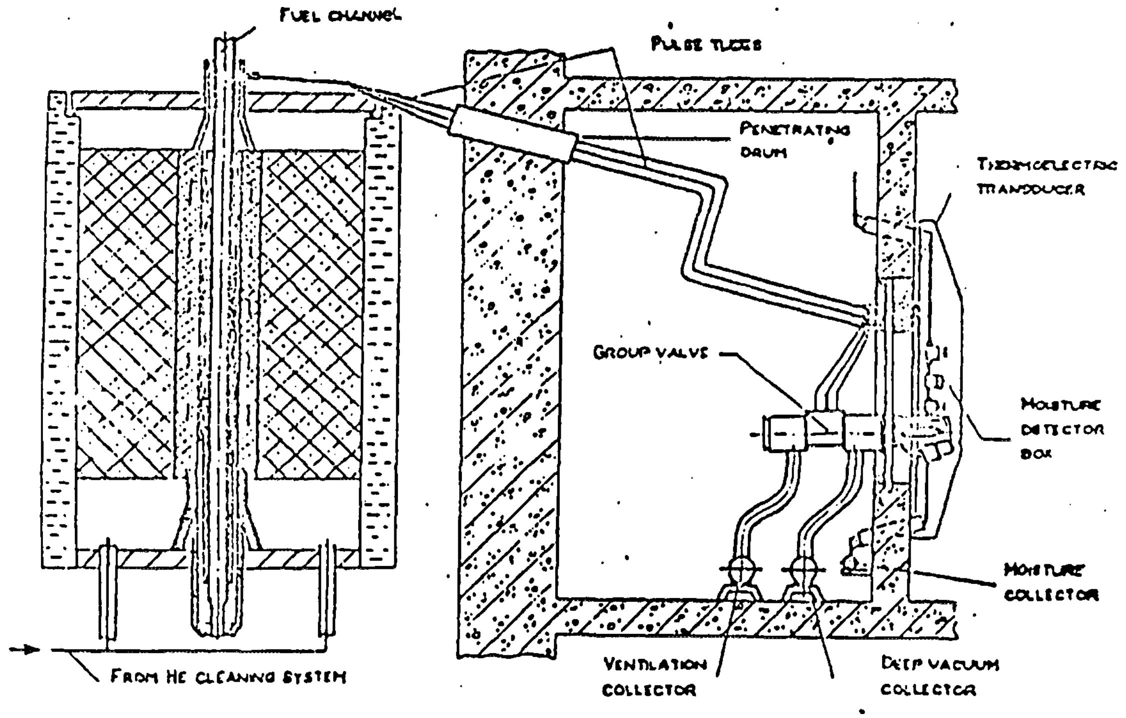


Fig.5 FUEL CHANNEL INTEGRITY MONITORING SYSTEM

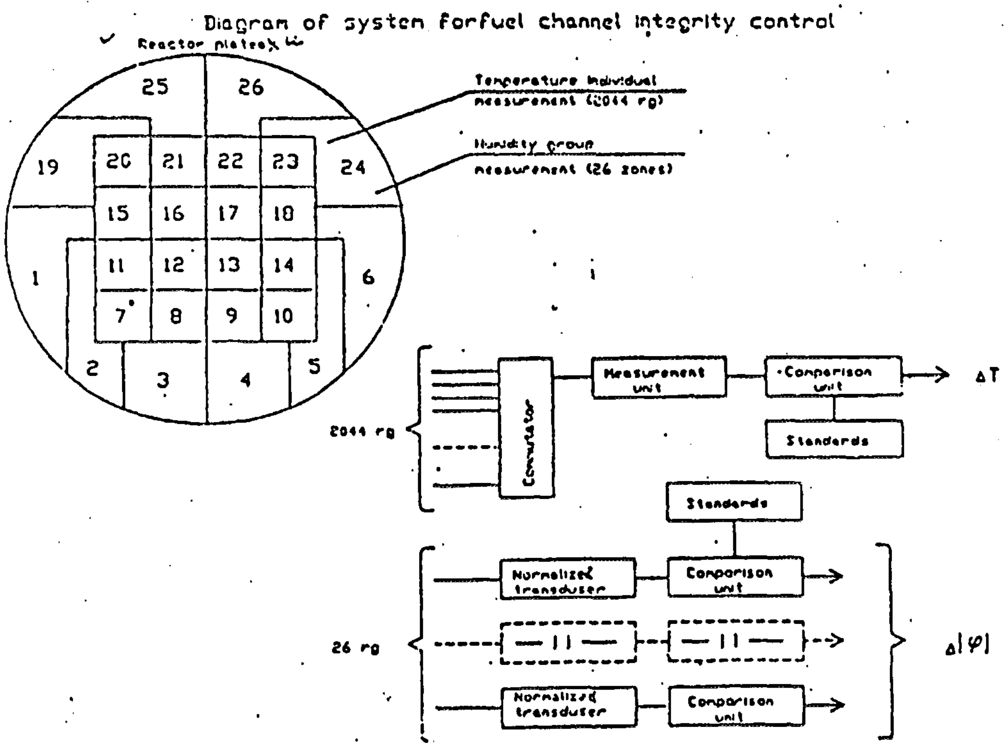


Fig.4

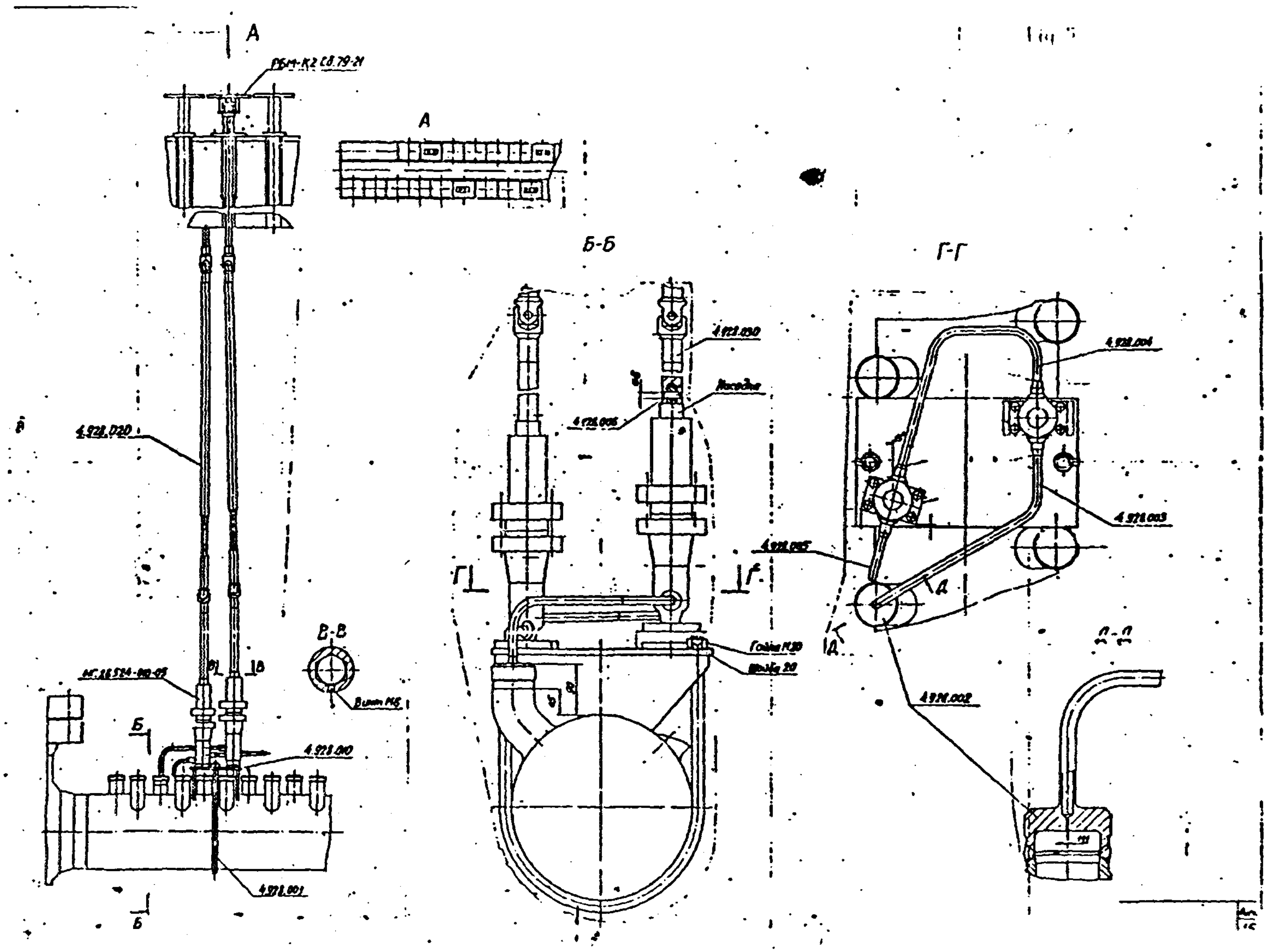


Fig 6   scheme of the leak-simulator stand

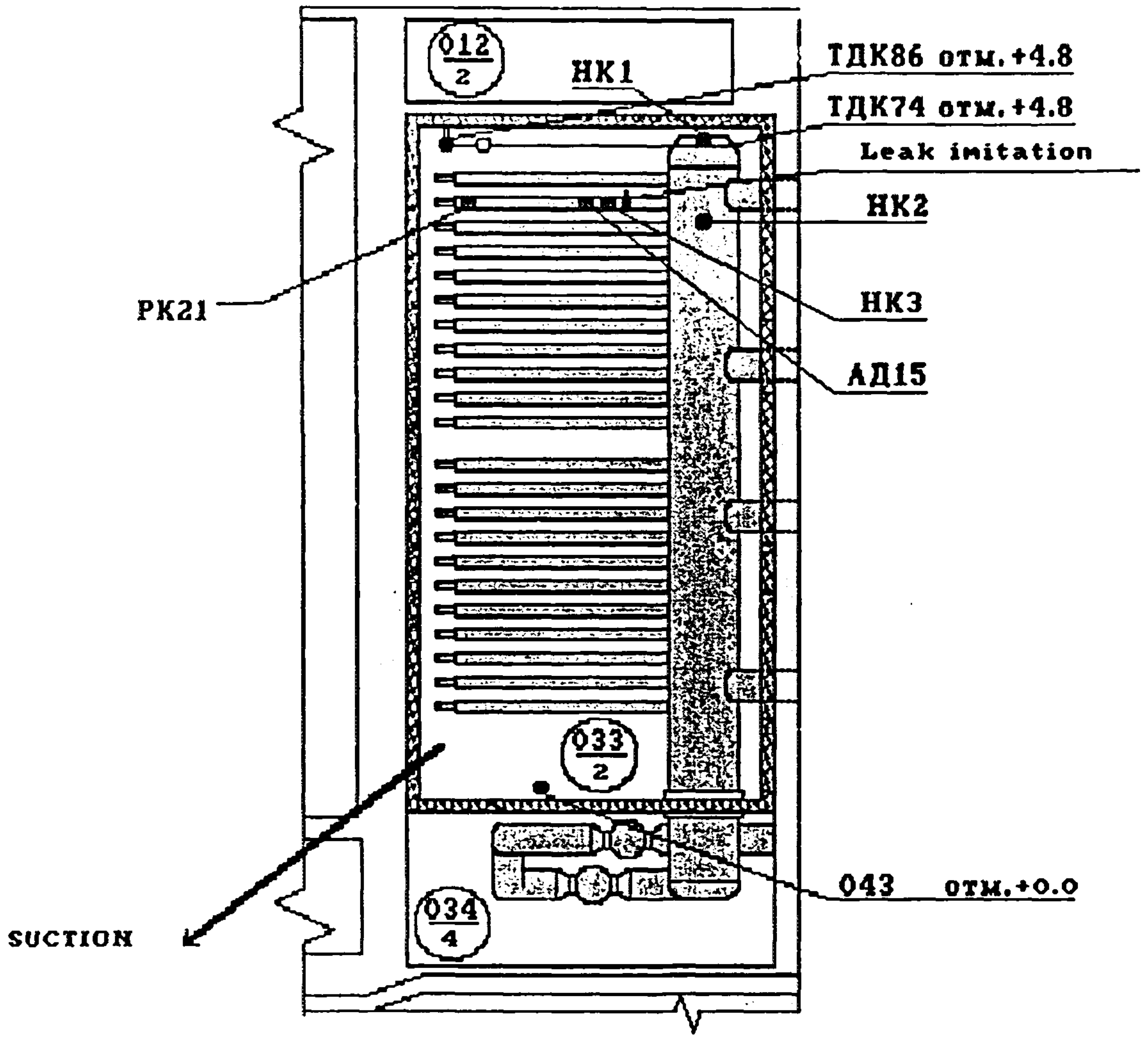
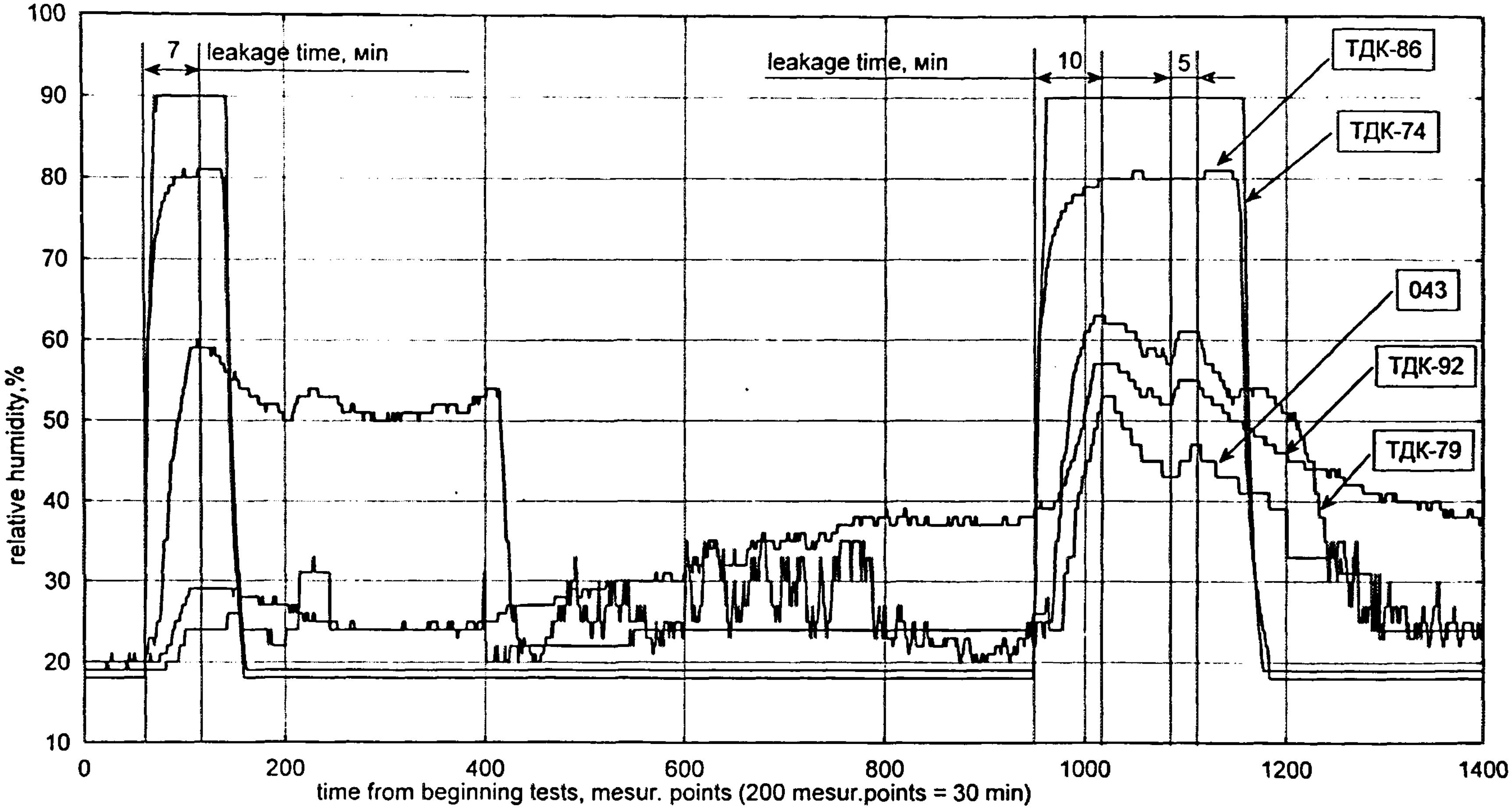


Fig. 5 The scheme of arrangement of acoustic sensor and sampling pipelines

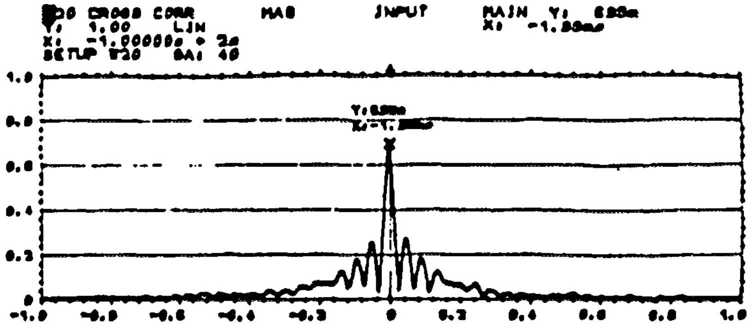
Fig. 7 Dynamics of relative humidity for sampling pipelines, 033/4 LNPP-2
during tests realization on leak-simulator, G=120 l/h, 02.12.94 17:49 - 21 - 26



Результаты взаимнокорреляционного анализа датчиков 2РК21, АД15, 2НК1

LNPP-2. P= 4 MPa. T = 60 C. PUMPS - stop

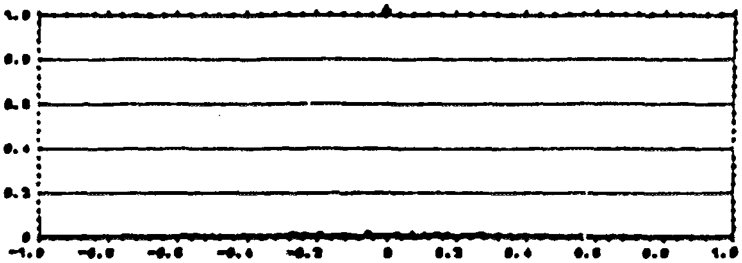
Течь открыта



channel A - 2PK21
channel B - AD15
F1=F2=80 kHz
F=3 kHz
Flp=100Hz

LNPP-2. P= 8 MPa. T = 270 C. PUMPS - in work. 440 MWt

Течь закрыта



LNPP-2. P= 4 MPa. T = 60 C. PUMPS - stop

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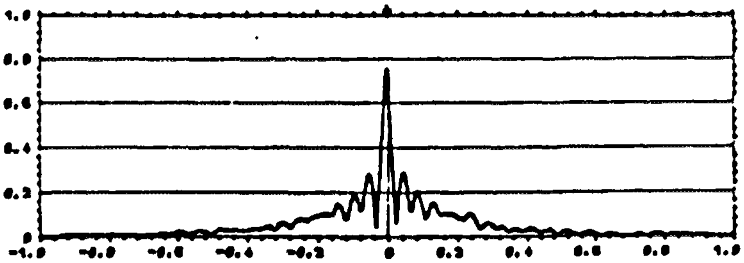


channel A - 2PK21
channel B - 2HK1
F1=F2=80 kHz
F=3 kHz
Flp=100Hz

LNPP-2. P= 8 MPa. T = 270 C. PUMPS - in work. 440 MWt

Течь закрыта

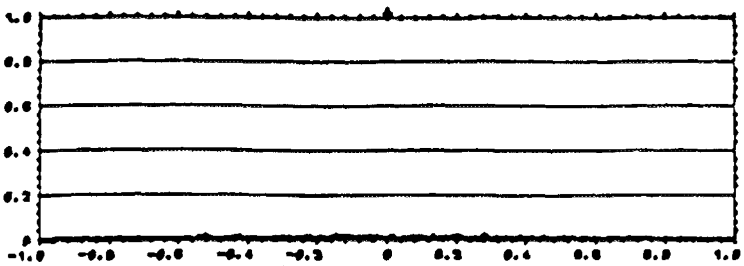


рис. 3

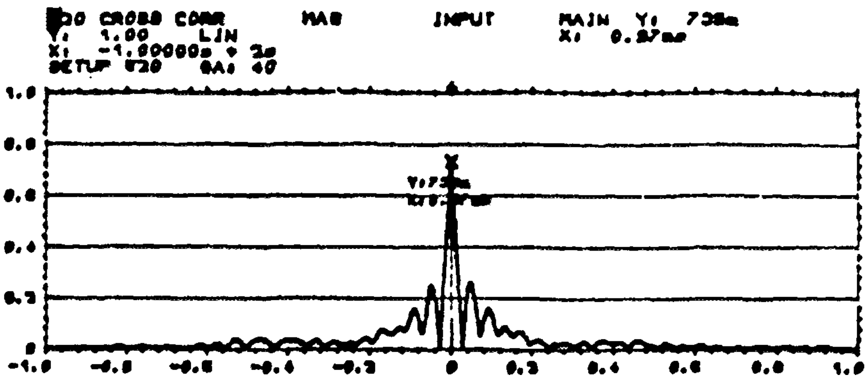
Fig. 8 The results of cross correlatoin analysis

Результаты взаимнокорреляционного анализа датчиков
2РК21, АД15, 2НК1

LNPP-2. P= 4 MPa, T = 80 C, PUMPS - stop

channel A - 2HK1
channel B - AD15
F1=F2=80 kHz
F=3 kHz
Flp=100Hz

Течь
открыта



LNPP-2, P= 8 MPa, T = 270 C, PUMPS - in work, 440 MWt

channel A - 2HK1
channel B - AD15
F1=F2=80 kHz
F=3 kHz
Flp=100Hz

Течь
закрыта

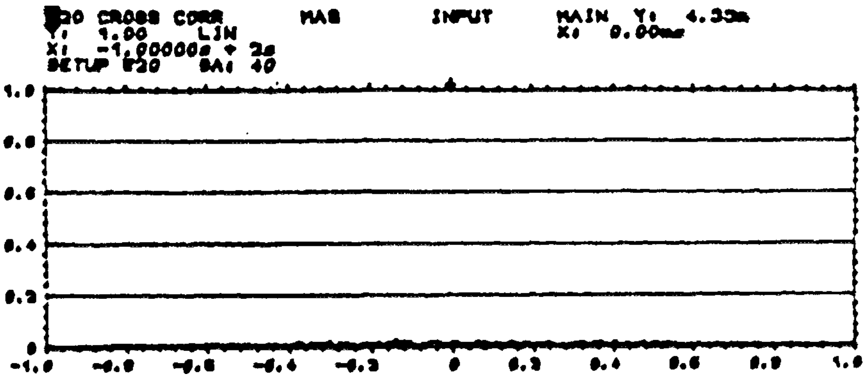
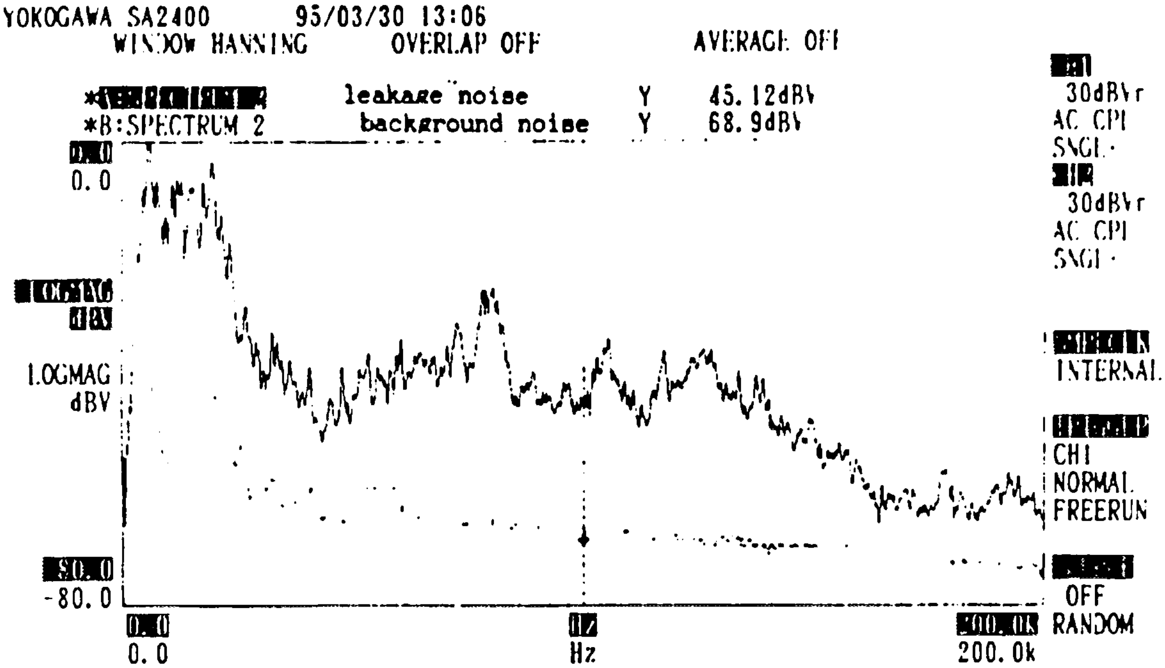
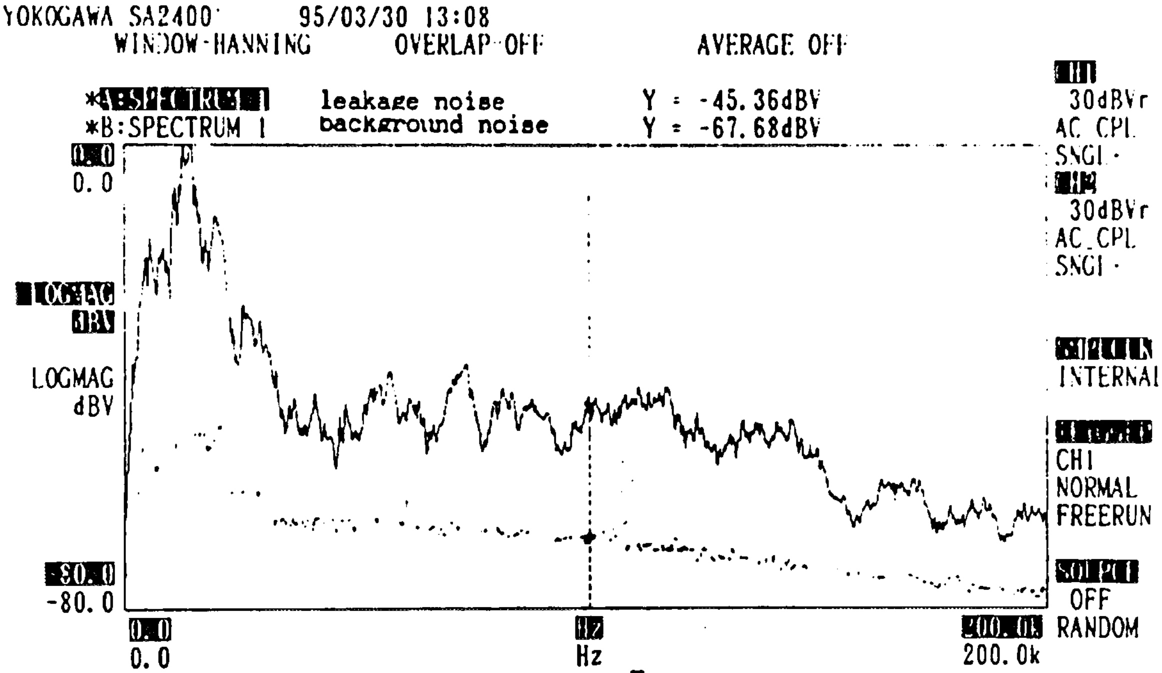


Fig 9 The results of cross correlation analysis for sensor 2HK2 and AD15

LNPP-2. P= 4 MPa. T = 60 C. PUMPS - stop



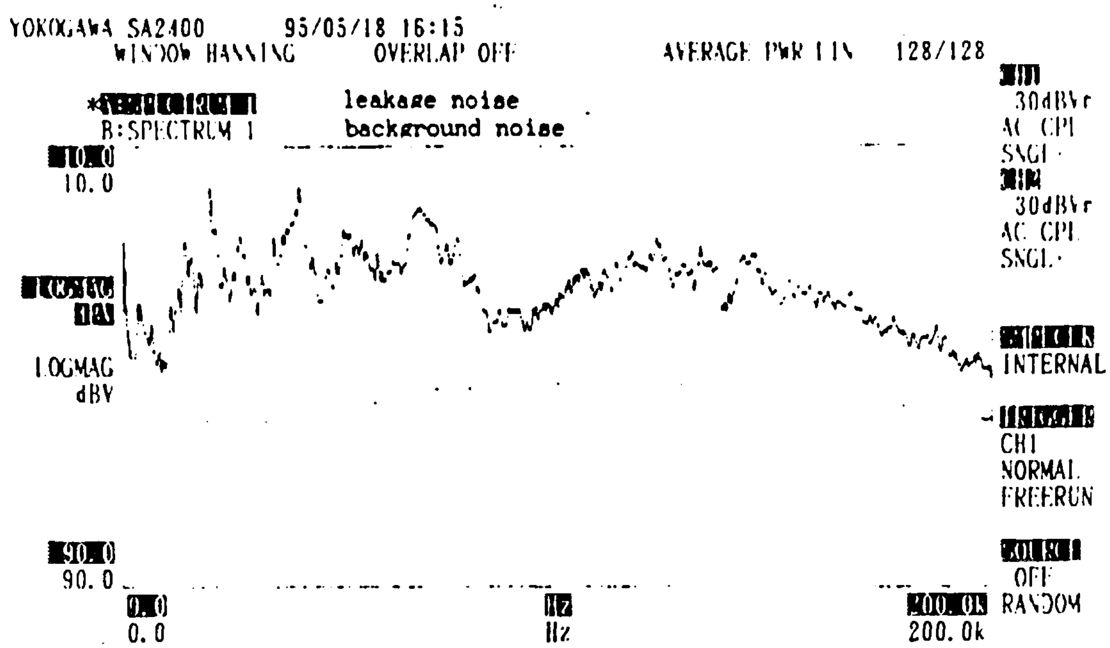
FOR SENSOR 2HK1



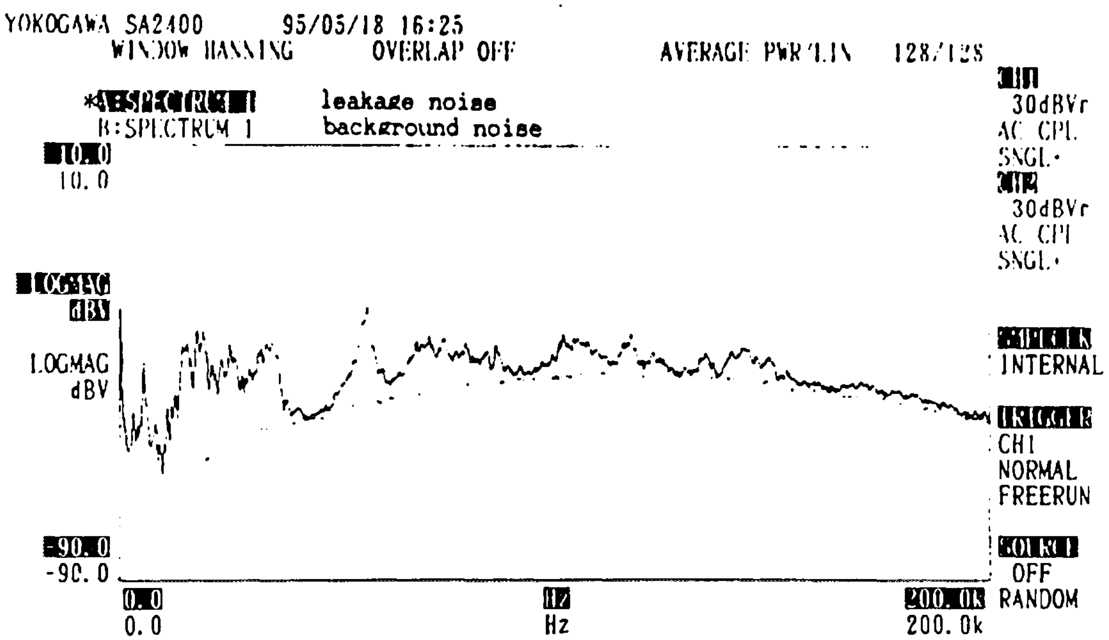
FOR SENSOR 2PK21

Fig 10 The leakage spectrum for sensor 2Pk21 and 2 HK1

LNPP-2. P= 4 MPa. T = 60 C. PUMPS - stop



FOR SENSOR 2HK2



FOR SENSOR AD15

Fig .11 The leakage spectrum for sensor 2HK2 and AD15

A9743561

FAULT DETECTION USING PARAMETER TRANSFER FUNCTIONS

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ABSTRACT

To reduce the number of alarms in NPP many techniques have been proposed for process monitoring and diagnosis. The object of our investigation is a dynamic process with digital signals. The general parametric model defines the transfer function form and it covers all dynamic characteristics between two monitoring parameters. To determine the proper model coefficients we are using recoursing least square methods. The transfer function coefficients define the correlation between two variables in desired time period. During process monitoring just the relation is observed because the number of coefficients and the structure is predefined with transfer function form. During plant operation the transfer functions for important parameters must be calculated and estimated. The estimated values are input parameters for an analytical algorithm. It determines which part of system causes the transient and recognises it. The proposed methodology allows a computer to monitor the system behaviour and to find out the most probable cause for abnormal condition.

1. INTRODUCTION

Computing techniques allow rapid data processing and permit development of real-time fault detection systems. They are executing during normal and abnormal conditions and help the operator to find out faults significant for safe reactor operation. Conventional systems use limited testing methods for abnormal conditions detection. An operator is notified when a measured parameter exceeds a predefined setpoint. However, it is not necessary that an exceeded parameter is directly linked with faults. Usually exceeded parameter triggers an alarm and then the operator has to diagnose the alarm cause. To reduce the number of alarms many techniques have been proposed for process monitoring and diagnosis.

In the paper [1] many approaches for fault detection and isolation are reviewed. They base on residual generation and their differences are in methods to generate it. In first few steps our approach for fault detection follows one of basic concepts, "parameter identification approach", mentioned in this paper. Both approaches use algorithm for parameter identification. Though our method uses calculated parameters as inputs for transient diagnosis instead for residual generation. The paper discusses the possibility how to apply the suggested methodology on simple mathematical model of the system controlled by one Proportional-Integral (PI) controller.

2. METHODOLOGY

The purpose of our investigation is to establish the methodology to distinguish causes from consequences when steady state conditions are degraded and a transient begins. The method described uses the fact that faults of a dynamic system are reflected in physical parameters. The idea is to detect the faults via estimation of the parameters of the transfer functions (mathematical models). To determine proper model coefficients recoursing least square method is used as technique for process identification. During process monitoring just the relation is observed because the number of coefficients and the structure is predefined with transfer function form. The method is based on time depended data of the system. Flow chart on figure 1 describes the suggested methodology.

In the first step identification algorithm on data is performed and transfer functions between selected parameters are calculated. In the second step we determine the meaning of transfer functions and assign them one value from a fuzzy set. In the next step a sequence of fuzzy values is analysed with the analytical algorithm. It determines the expected system responde on transient initiation or the cause for abnormal system behaviour.

2.1. System identification

Several techniques for process identification have been proposed [2]. They depend an on signals and process types. In our case the object of investigation is a dynamic process involving digital signals. We want to define relationships between various selected parameters in the observed dynamic system. The relation is determined by transfer function written as difference equation. The general parametric model defines the linear transfer function form (equation 1). This form must cover all dynamic characteristics of two monitored parameters.

$$G(z) = K_s \frac{b_0 + b_1 z^{-1} + b_2 z^{-2} + \cdots + b_n z^{-n}}{1 + a_1 z^{-1} + a_2 z^{-2} + \cdots + a_m z^{-m}} \tag{1}$$

The system is observed on-line in real time. Recoursing methods are suitable for identification. Proper model coefficients are set by recoursing least square method [2]. The transfer function coefficients define the correlation between two variables in a desired time interval. Values of coefficients could be different but still describe the same behaviour.

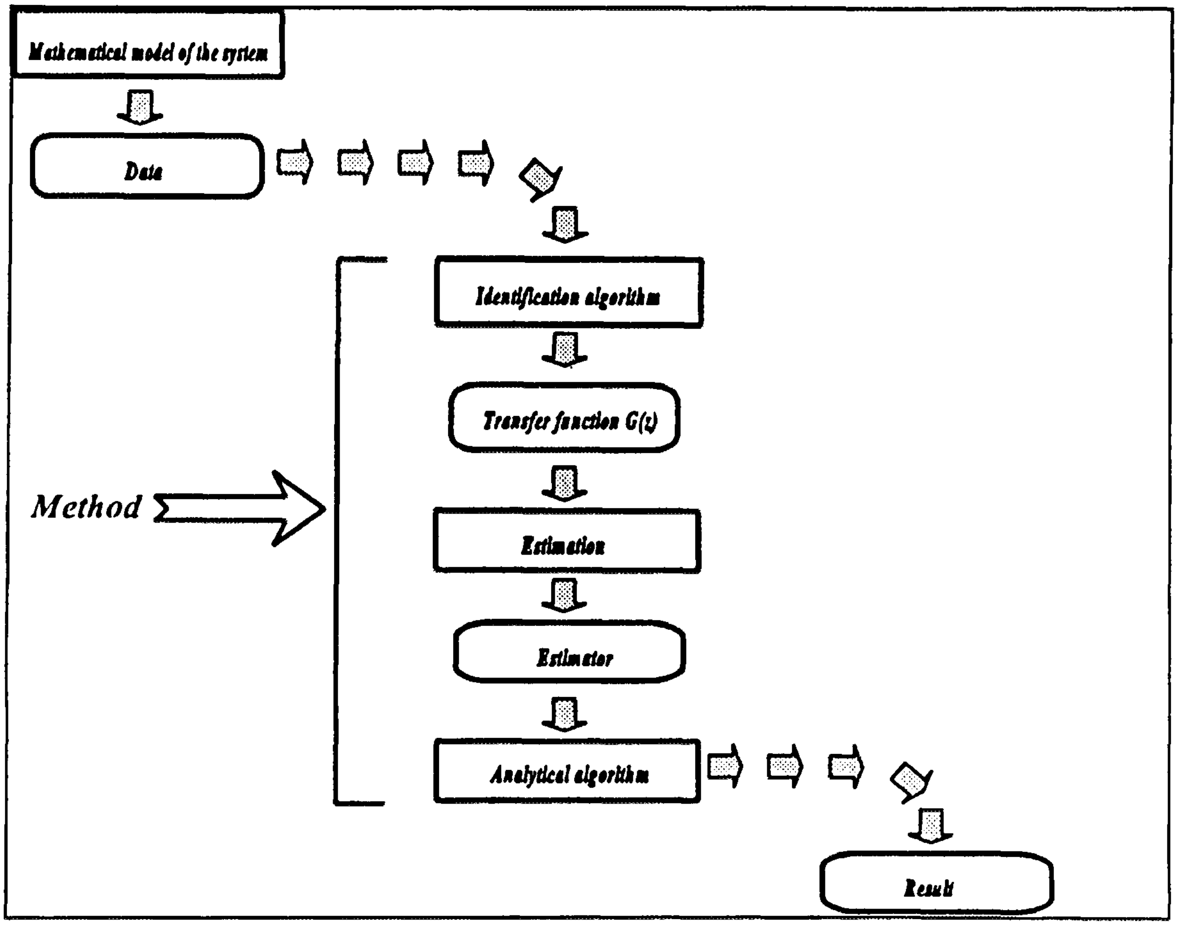

Figure 1: Flow chart of method

2.2. Estimator

Next step during system behaviour detection is to determine meaning of the transfer function. To understand the meaning of the relation between coefficients we declare the corresponding estimator. Meaning and type of estimator may be different, depending what kind of estimating they perform. The number of inputs and outputs may be different. Sometimes the estimator gives the final result such as "valve error", but usually the result is just one value from fuzzy set: increasing, decreasing, stable.

We assume that the observing system has recognized steady state when we start monitoring. When significant change in the system appears, the automatic monitoring system must detect and mark it as transient. Three different transfer functions were analysed. We have tried to define an additional parameter that converts coefficients into one single value. This procedure of estimation produces parameter known as the estimator that joins the major information of transient at desired time. In the paper [3] is described simple estimator for transient detection based on residual. The purpose of it is to determine the cause of the transient in the pressurizer. In our case we have done estimation direct from coefficients of transfer function without residual generation.

The estimator form is dependent on type of transfer function. First we define following predefined transfer function (equation 2) for identification:

$$G_{ident}(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 - z^{-1}} = \frac{Y(z)}{U(z)} \tag{2}$$

At the beginning the observed system is in steady state and its parameters have constant values. Because we want to detect and recognise the transient, only the parameter variation from the steady state is measured. The difference form for equation (2) is for the input written as

$$\begin{aligned} \Delta y(k) - \Delta y(k-1) &= b_0 \cdot \Delta u(k) + b_1 \cdot \Delta u(k-1) + b_2 \cdot \Delta u(k-2) \\ u(k) &= u_{00}(k) + \Delta u(k) \\ y(k) &= y_{00}(k) + \Delta y(k) \end{aligned} \tag{3}$$

Parameter u_{00} represents the steady state value and Δu the difference between the steady state and the present value for the k^{th} input parameter. The same form is used for the output parameter (y_{00} and Δy).

The correlation between two parameters is written as transfer function (b_0, b_1 and b_2). Equation (3) shows that only influence of an input parameter on an output parameter is measured. In the case that output parameter has changed ($\Delta y(k)$ is not equal zero) and the input parameter has not changed ($\Delta u(k)$, $\Delta u(k-1)$ and $\Delta u(k-2)$ are equal to zero) then the transfer function coefficients could have any value. We can conclude that input parameter does not cause the change of an output parameter and here we put the coefficients (b_0, b_1 and b_2) value to zero.

To determine the correct estimator one must find a suitable mathematical relation between coefficients of the transfer function. Equation (2) could be divided into three parts: proportional, integral and differential.

$$\begin{aligned} G_{ident} &= K_p + \frac{K_i}{1-z^{-1}} + (1-z^{-1}) \cdot K_d \\ K_p &= -b_1 - 2 \cdot b_2 \\ K_i &= b_0 + b_1 + b_2 \\ K_d &= b_2 \end{aligned} \tag{4}$$

The integral part is very interesting because we are looking for mathematical term to identify influence of input parameter on output parameter. If we write the integral part of equation (4) in difference form we get the equation (5).

$$y(k) - y(k-1) = K_i \cdot u(k) \tag{5}$$

The equation shows that change of the output further depends on the input and its gain coefficient K_i. We assume that if we calculate transfer function between two parameters and sum all its coefficients into one value (K_i), then this value may be used as a measure how input influences the output. The adequate estimator ($Estim_x$) is determined as

$$
\begin{gathered}
Estim_x = | b_{0_x} + b_{1_x} + b_{2_x} | \\
If\ (Estim_x > E_{treshold})\ Then\ Estim_x = 1\ Else\ Estim_x = 0 \\
E_{treshold} \ \ldots\ estimation\ sensitivity \\
x \ \ldots\ i^{th}\ transfer\ function
\end{gathered}
\tag{6}
$$

Finally all estimators ($Estim_x$) for all transfer functions are joined into one value (Estim). To mark individual parameter activity during transient the binary coding has been used as follows

$$
Estim = \sum_{x=0}^{N-1} 2^x \cdot Estim_x \tag{7}
$$

During the system monitoring procedure every data sample is extended with an additional parameter Estim. It contains data about dynamic behaviour of system parameters. The faults or system unusual behaviour may be detected by an algorithm based on Estim parameter.

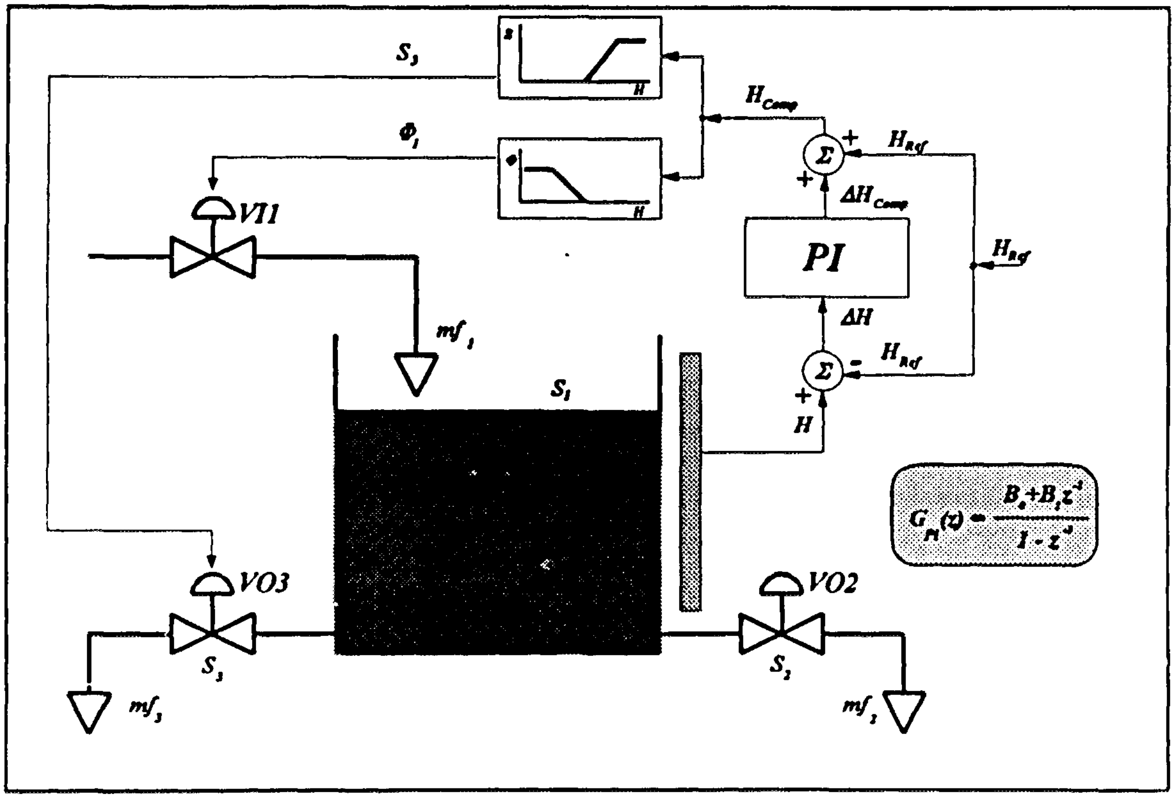

Figure 2: Observed system (water storage tank)

2.3. Analytical algorithm

Analytical algorithm for fault or system unusual behaviour detection strongly depends on the observed system. It is composed of different rules based on previous knowledge and experience gained about the system.

As a test the case a water storage tank was selected as the monitored object. The mathematical model of natural relation between parameters of this system is straight forward. PI (Proportional-Integral) controller has been added to reduce the steady state error after transient. The model serves just for data generation during transient initiation. Figure 2 shows its construction of the system selected for the case study.

It is assumed that the system requires constant mass flow through valve VO2. To assure constant mass flow through it the water level must be kept at some level. For this reason the control system with PI controller and two valves VI1(to add water) and VO3 (to remove water) have been added.

Four parameters have been observed:

- water level (h_w)
- mass flow through valve VI1 (mf_1)

- mass flow through valve VO2 (mf_2)
- mass flow through valve VO3 (mf_3)

Algorithm must recognise the steady state values for all four parameters (h_{w00}, mf_{100}, mf_{200}, mf_{300}). We assume that if a parameter does not change in ten seconds then its present value corresponds to its steady state condition.

The critical parameter in observed system is the water level. We assume that all faults will be reflected on the level behaviour. Three parameters influencing transfer functions have been calculated as show in table 1.

Table 1: Input and output parameters for transfer functions

input parameter	output parameter	transfer function name	estimator
mf_1	h_w	TF_1	$Estim_1$
mf_2	h_w	TF_2	$Estim_2$
mf_3	h_w	TF_3	$Estim_3$

Four different system states have to be detected:

- steady state; (DSS)
- system transient as demand for increasing or decreasing output flow mf_2; (DST)
- leak; (DLS)
- other transients; (DO)

The steady state is detected and confirmed when Estim value is equal to zero. This means that none of the observed parameter changed from its steady state value. Expected transients, such as a demand for increasing and decreasing output mass flow, are reflected in changes of mf_2 and mf_1 or/and mf_3. In case of a leak from the tank only the mass flow mf_1 will increase to compensate for the lost water. In table 2 roles for system behaviour diagnose are showed.

At the beginning and at the end of a transient the estimator does not give a clear picture of the basic transient, but more or less shows which parameter initiates the transient or mitigates the consequence of it. We have performed one simple rule to recognise the main transient. The basic diagnosis of DST and DLS have been made favourite. That mean if DST and DLS had been diagnosed from previous data, then diagnosis cannot be changed for next sample except, if the parameter Estim has been equal to zero in last ten data samples (system had returned to new or previous steady state). The last rule helps to detect the end of a transient.

Table 2: Roles and relations for system behaviour diagnose.

$Estim_1$	0	1	0	1	0	1	0	1
$Estim_2$	0	0	1	1	0	0	1	1
$Estim_3$	0	0	0	0	1	1	1	1
Estim	0	1	2	3	4	5	6	7
Diagnosis	DSS	DLS	DO	DST	DO	DO	DST	DO

With more sophisticated construction of an analytical algorithm also other conclusion could be made such as sensor fault, size of leakage, etc. The final diagnosis could be checked by testing conditions at the beginning and in the end of transient.

3. CASE STUDY

Three calculations were performed for three different transients to test the proposed methodology: demand for decreased and increased output mass flow and leakage. First data have been collected in steady state conditions from mathematical model (described in a previous chapter). After some time the transient has been initiated. Measured parameters have been estimated continuously during steady state and transient.

Parameters initiating the transient had been changed in three different ways:

- step
- linear
- exponential

3.1 Output mass flow decreasing

The cross section in out flow valve VO2 has been decreased from 0,01 m^2 to 0.0002 m^2 in fifty seconds. Change of valve cross section has caused a decrease of output mass flow mf_2 from 0.14 kg/s to 0.0025 kg/s.

In all three cases the water level has increased and the mass flow mf_1 has decreased. When the transient has been initiated as step change the water level had increased so high that valve VO3 had been opened for some time period to release additional water from the tank. In next few seconds water level had decreased too low and some correction had been done by opening the valve VI1. During linear change of output mass flow the same correction had been made.

For all three simulated cases algorithm has recognised the correct transient. Annunciator of a transient during step change has been displayed twice as long because control system needed more time to solve the problem. Time depended graphs for this example are on figure 3.

3.2 Output mass flow increasing

This case is the same as in the previous except that the cross section in valve VO2 has been increased from 0,01 m^2 to 0.0199 m^2 and that has leaded to increase output mass flow mf_2 from 0.14 kg/s to 0.28 kg/s. In all three cases the water level has decreased and the mass flow mf_1 has increased. The valve VO3 has stayed close during transient.

Algorithm has recognised the correct transient. Announcement for transient during linear change has been displayed a little longer because control system has followed demand for increasing mass flow from the system and in the end it has made some over shooting. Time depended graphs for this example are showing on figure 4.

3.3 Leak

In last example an orifice has been added into tank shell. Through this orifice the water has been leaked from a tank in three different ways as it has been described. The valve VO3 has stayed closed during the transient and no change on mass flow mf_2 has been detected. Only the change in water level and mass flow mf_1 have been detected.

In this case the algorithm has recognised the correct transient too. Announcement for transient during step and linear change has been displayed mostly the same time. During exponential change the algorithm has announced twice that transient has appeared. After few seconds when the transient had appeared the control system has caught dynamic nature of orifice increasing and the system status has been recognised as steady state very soon. Some time later the orifice had increased slower and the algorithm has detected leak again. Time depended graphs for this example are showing on figure 5.

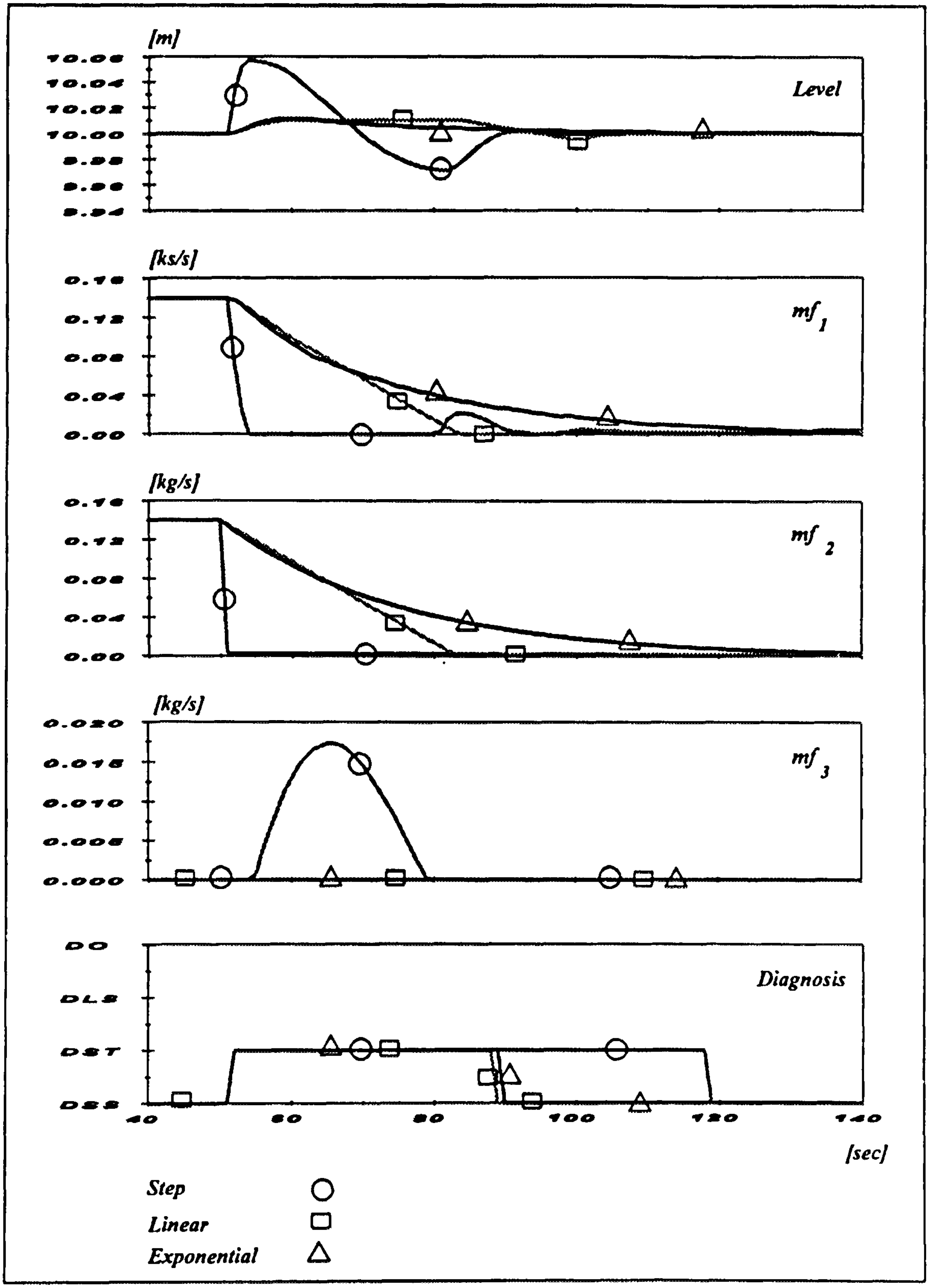

Figure 3: Output mass flow decreasing

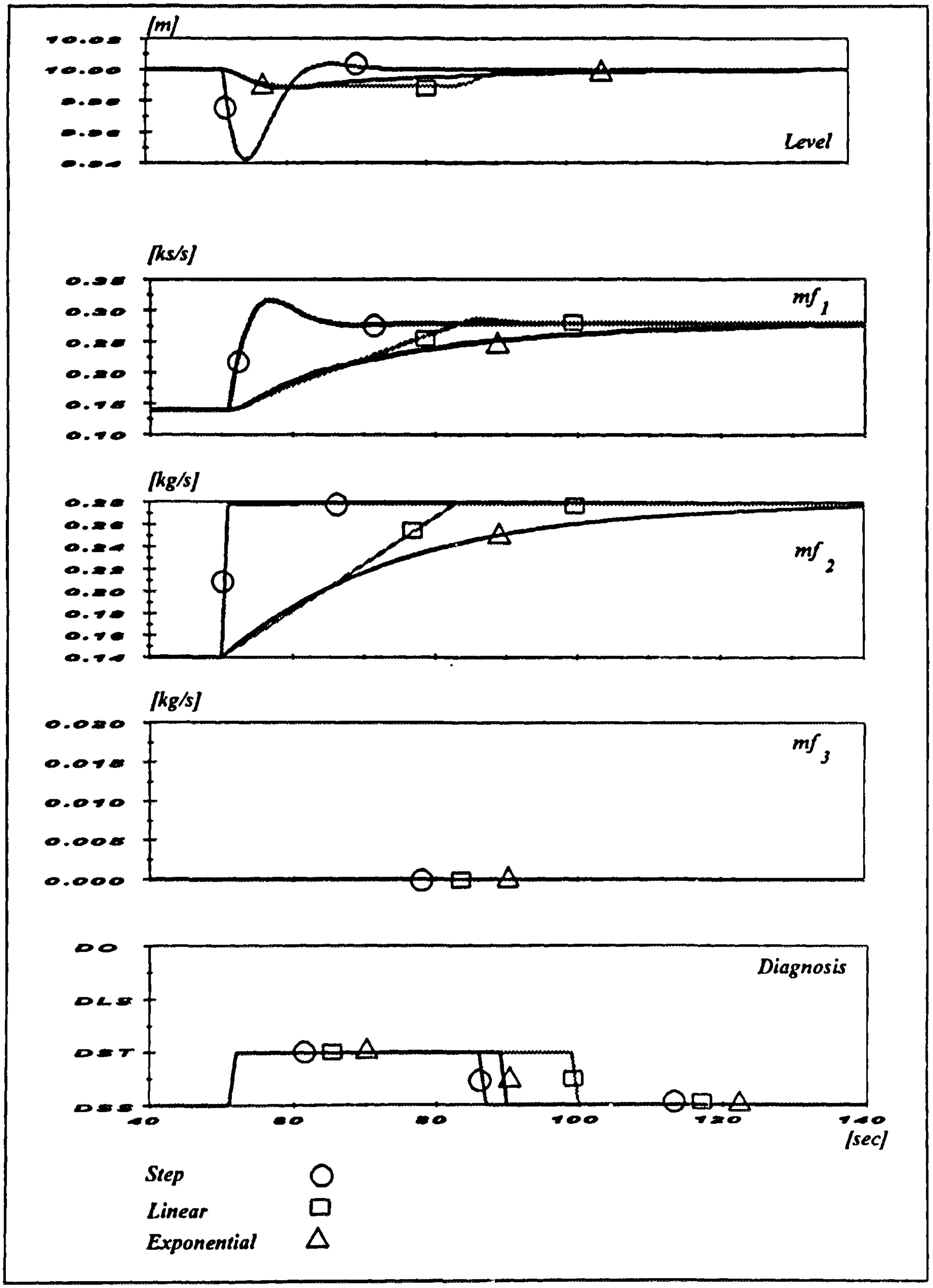

Figure 4: Output mass flow increasing

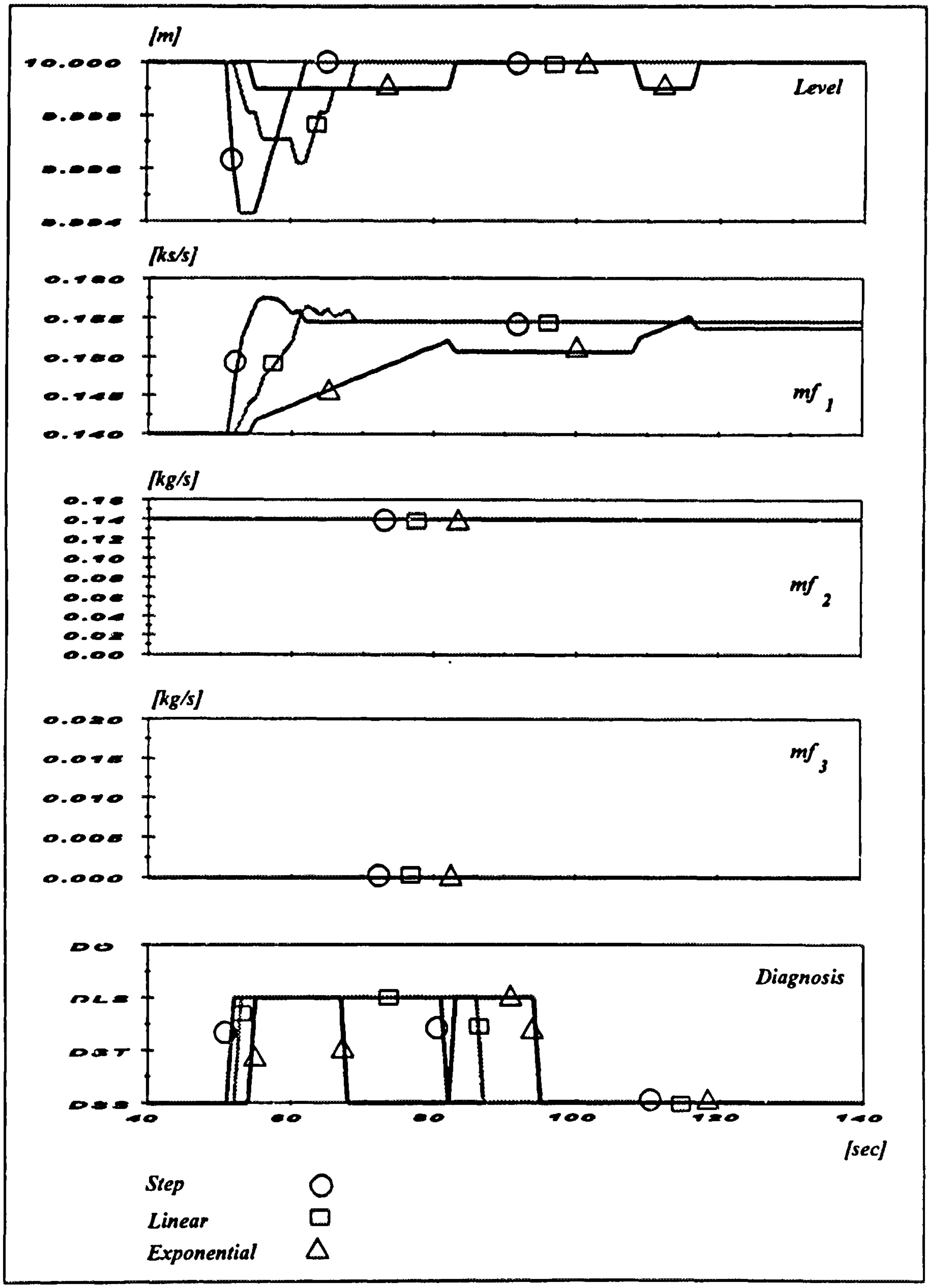

Figure 5: Leak

4. DISCUSSION

Data written as time depended graphs are very suitable for humans but its form has little value for computer processing. All computer codes for system diagnostic are written by human and they are using the human way of thinking which is based on data form suitable for them. A good example is Emergency Operating Procedures. During monitoring the operator must compare the terms like: increasing, decreasing, stable, stable in some limits, unstable, etc.. That approach gives expert more space to write more flexible diagnostic system but data acquisition system in the plant deals just with the real numbers. When the computer has to perform the diagnostics, it must convert that into fuzzy set chosen by the expert.

The purposed approach is based on transfer function between two parameters. Its coefficients describe dynamic relation of two parameters in a defined time period. When graph shape is changed, the values of coefficients change too. The set of values in time interval for input and output parameters are converted in few or more less constant values. They are very suitable for analysis with mathematical operators such as: equal, nonequal, higher, smaller, etc. It is suggested to use different estimators to determine the meaning of a transfer function. With proper estimators computer code can automatically determine the relation between two parameters, analyse all relations and announce to the operator that some change has occurred in the observed system. The goal of proposed method is to allow a computer to monitor the system behaviour and to find out the most probable cause for transient.

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RELIABILITY OF OPERATING VVER MONITORING SYSTEMS

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ABSTRACT

The elaboration of VVER monitoring systems reliability measures is described in this paper. The evaluation is based on the statistical data about failures what have collected at the Ukrainian operating nuclear power plants (NPP). The main attention is devoted to radiation safety monitoring system and unit information computer system, what collects information from different sensors and system of the unit. Reliability measures were used for decision the problems, connected with life extension of the instruments, and for another purposes.

1. INTRODUCTION

NPP with pressurised water reactors VVER-1000 are the most wide - spread in the Ukraine : now 11 from 15 Ukrainian units are operating in the Ukraine, include unit 6 Zaporozhye NPP, what started in the end of 1995. The instrumentation and control systems (I&C) of all unit VVER-1000 type V-302 and V-320 in the Ukraine, Russia, Bulgaria was created by similar typical design. This design was fulfilled in 1980-1982, and after that monitoring systems had only nonconsiderable modemisation.
In spite of the spreading of VVER-1000 and long time of operation of these units, reliability measures of their I&C are not published. This confirmation relates to monitoring systems. Short information about reliability analysis of these systems was published only in [1].

The goals of this investigation were:
- evaluation of the reliability measures of the instruments (different types of sensors, computers, etc.) and the monitoring systems, what are operated at the Ukrainian NPP-1000;
- elaboration of the recommendation about reliability assurance;
- analysis of instrument failures point stochastic processes, including analysis of the trend in these processes for definition of possibility of life extension;
- comparison between reliability measures in technical specifications and standards with reliability measures, what were received in the operating conditions. (According to USSR standards, what now acted in the Ukraine, requirements to reliability measures have to include to technical documentation of different industrial instruments and systems. These requirements take place for different NPP I&C systems - not only for Safety systems).

Data bases about NPP I&C reliability have elaborated and supported in Department "I&C NPP reliability" of Ukrainian Scientific Technical Center of Nuclear and Radiation Safety. In present time, Ukraine has not common systems for collection and analysis of information about reliability of different NPP equipment (similar for example, NPRDS in the USA). General system for collection information about reliability of different NPP equipment will be created in the Ukraine in 1996-1998.

Information in our base was received from NPP documents, what are destined for managing of operation, but not especially for collection of information about failures. We only fulfilled some actions for improving of authenticity of this information. The collection of information about failures took place during some years.

The main attention in this paper is devoted to two systems - radiation safety monitoring systems and unit information computer system. Radiation safety monitoring system (type - ÀÊÐÁ-03) realise monitoring of the following parameters:
- water volume activity in the circuits, the water body and the tanks;
- aerosol volume activity in the compartments;
- steam and air mixture volume activity in the releases of the turbine;
- gas volume activity;
- neutron and gamma - quantum fluxes from the circuits;
- gamma radiation dose rate, etc.

Structure schema of this system is shown at fig.1.

Unit information computer systems type "Complex-Titan 2" collect information from different sensors of temperature, pressure, difference of pressure, level, etc., of main technological equipment and from different systems, including in-core reactor monitoring system. Structure schema of "Complex-Titan 2" is shown at fig. 2.

Both systems were created by same principal: hierarchical closed structure without computer nets.

2. RELIABILITY OF THE INSTRUMENTS

Reliability measures of the instruments, what include in radiation safety monitoring system, are shown at fig. 3. Reliability measures of instruments, what include in unit information computer system, are shown at fig. 4.

Reliability measures at fig. 3-4 are average for all systems at the Ukrainian NPP. The reliability measures of any identical instruments had essential difference for different units and plants. The reasons of this difference caused by the different quality of the manufacture, setting, maintenance and statistical straggling.

The analysis of the failures point stochastic processes showed, that there was the infant mortality time for many types of the instruments. The value of this time equals 0,5-1,5 years, as rule. This analysis also showed, that the hypothesis about the aftereffect absence was not confirmed in many cases. The relation between the dispersion of the number of the failures and the mean of this number is not equal to 1, as in the Poisson process, and equals 2-4. One of the classes of these processes is the twice stochastic Poisson process (D.Cox process [2]), which has essential aftereffect. The failure intensity of this process in each it's realization is, the in turn, a realization of some other stochastic process. We proposed the common model of this process and some particular cases [3].

The collected information was used for decision of the tasks, connected with the life extension of the instruments. The life extension problem of Ukrainian NPP instruments is particularly important because the following reasons:
- the regiment Soviet instruments durability measures equaled 8-10 years: this is less then durability measures of whole NPP;
- the ageing of the instruments are equal of the ageing the technological eguipment, and many instruments are near to end-of-installed life or exceed to this value ;
- the instruments manufactures are located in Russia and other countries of former USSR; the economic connections with these countries are very hard now;
- the instrument cost for replacement grows faster than the inflation;
- the USSR designers and producers determined the durability measures without sufficient tests and basis.

STRUCTURE SCHEMA OF RADIATION SAFETY MONITORING SYSTEM ÀÊÐÁ-Ï3

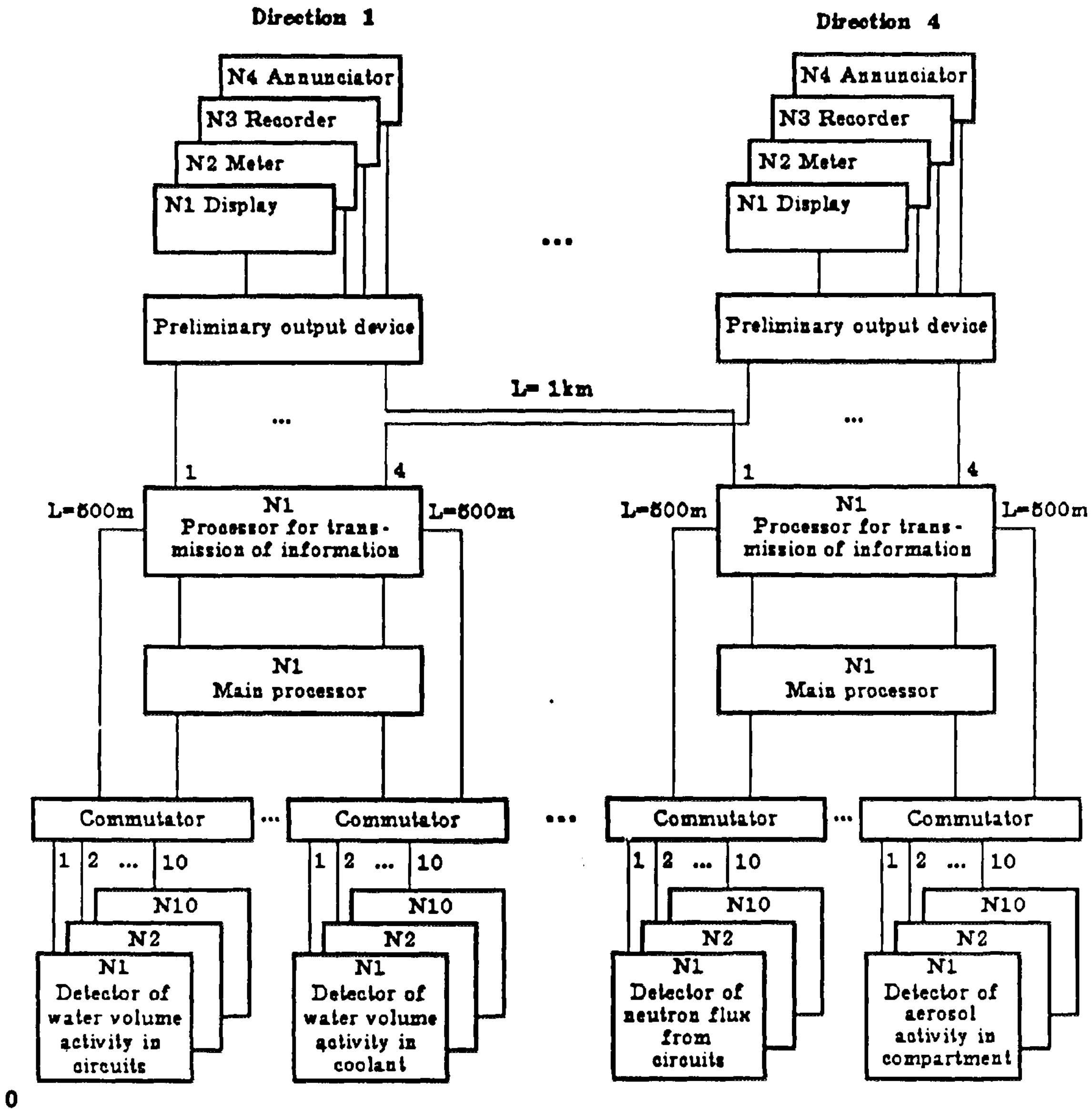


Fig.1

STRUCTURE SCHEMA OF UNIT INFORMATIONAL COMPUTER SYSTEM "COMPLEX-TITAN 2"

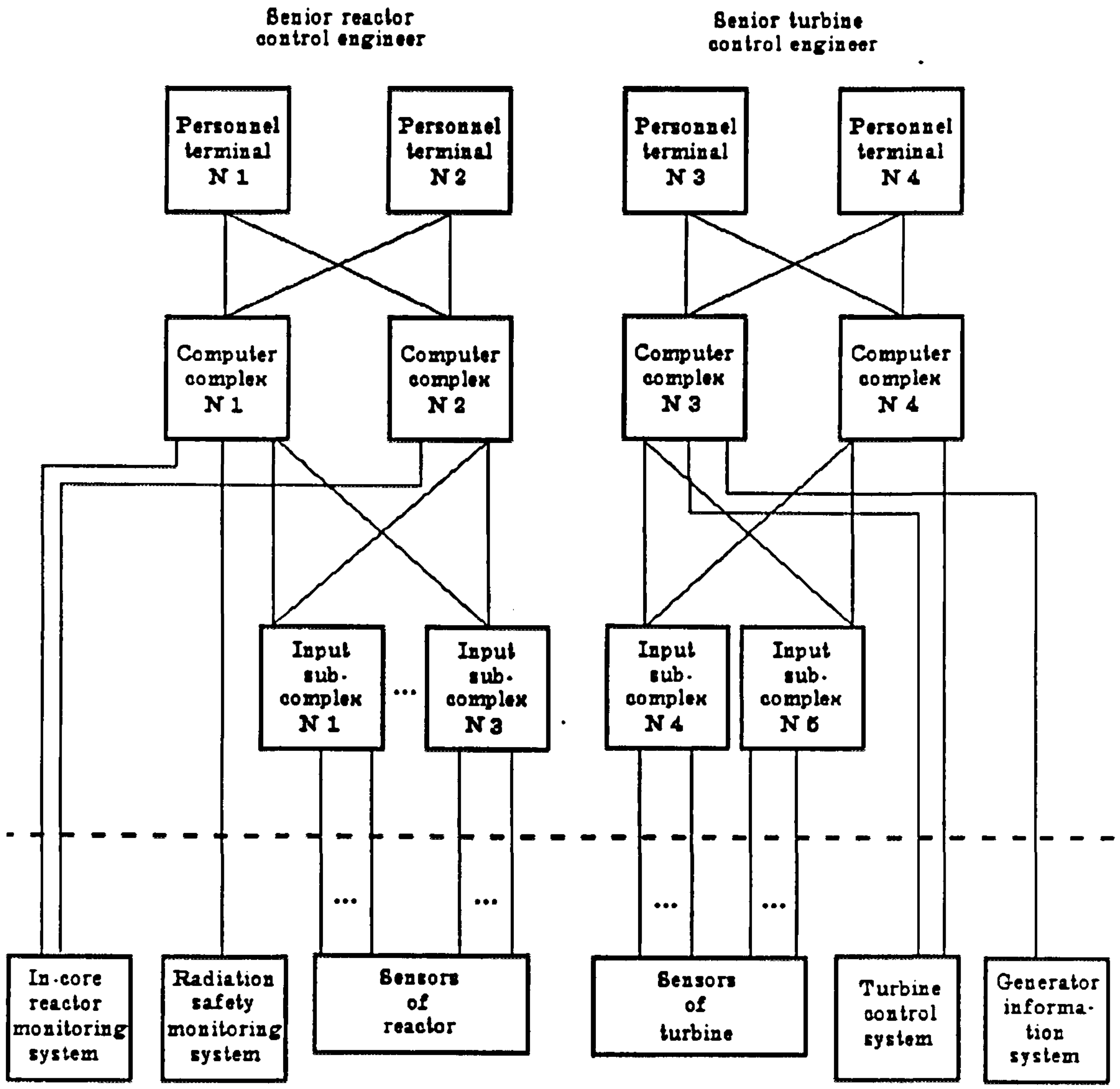


Fig.2

RELIABILITY MEASURES OF DEVICES WHAT INCLUDE IN REACTOR SAFETY MONITORING SYSTEM ÀÊÐÁ-03

Name of device	Type	Number of devices	Operating time, 10^3, h	Number of failures	MTBF, h
Detector for monitoring of neutron flux from circuits	ÓÄÈÌ-02	13	557	4	139000
Detector for monitoring of gamma-quantum flux from circuits	ÓÄÏÃ-03	16	1090	69	16000
Detector for monitoring of steam and air mixture volume activity in release of turbine	ÓÄÏÁ-03	28	977	22	44000
Detector for monitoring of water volume activity in circuits	ÓÄÆÃ-04	488	977	35	28000
Detector for monitoring of water volume activity in water bodies and tanks	ÓÄÆÃ-14	215	2430	140	17000
Detector for monitoring of aerosol volume activity in compartments	ÁÄÀÀ-05 ÁÄÀÁ-06	110 48	6240 1989	117 46	53000 43000
Detector for monitoring of gamma radiation dose rate	ÁÄÌÃ ÓÄÌÃ	1141 127	5330 3480	150 18	35000 193000
Detector for monitoring of gas volume activity in the systems for gas purification	ÓÄÃÁ	342	16700	297	56000
Commutator	ÓÁÀ-09	326	19600	65	301000
Main processor	ÓÏÎ-100Ì	29	1190	192	6200
Processor for transmition of information	ÓÈ-28	30	1322	122	10800
Preliminary output device	ÁÂÖ	127	4990	51	97800
Annunciator	ÁÂÉ - 13 ÁÂÈ - 12	276 1272	13800 52800	41 154	334000 342000
Display	ÓÂÊ-13	27	1050	52	20200
Meter	ÓÂÈ-09	10	737	22	33500

Fig.3

RELIABILITY MEASURES OF THE SYSTEMS

Name of function	Type of function	Criterion of failure	MTBF, h	Availability
RADIATION SAFETY MONITIRING SYSTEM ÀÊÐÁ-03				
Parameters measurement	Simple (channel)	Absence of indication about parameters	1700-2400	
Parameter annunciation	Simple (channel	Absence of annunciation about parameter or spurious failure	3200-4000	
INFORMATION COMPUTER SYSTEM "COMPLEX-TITAN 2"				
Technological parameters measurement	Composite Simple (channel)	Absence of indication about more, then 5% parameters during the time, more 10 min Absence of indication about parameter	8800 6300	
Technological parameters recording	Composite Simple (channel)	Absence of recording about more, then 10% parame-ters during the time, more 1 h Absence of recording about parameter	5300 2500	
Emergency situation recording	Composite	Absence of recording about more, then 5% events (parameters) during the time, more then 10 min	-	0,9993

Fig.4

Statistical processing of failures point stochastic processes was realized by the methods, described in books [2,4,5]. The processing included the statistical hypothesis test about absence of failure intensity growth, which showed the absence of the trending. (These imstruments and systems are restoration objects, and the failure intensity was choosed as main reliability measure for trending analysis).

The example of relationship between summary failure intensity and time for all components of information computer complex is shown at fig. 5a; the example of relationship between summary failure intensity and time for all components of radiation safety monitoring system is shown at fig. 5b. In fig.5 the fixed observation time corresponds to the different ageing of instruments because the different starting moments of the units and therefore of the instruments and systems.

The analysis of ageing showed that hypothesis about raising of the tranding of the point stochastic process was not confirmed for the most types of the instruments ; failures point stochastic processes are stationary for the investigation time range. The results of investigations showed, that lifetime may be extended for the most types of instruments.

Analysis of operating reliability is only a part of the working for elaboration of the instruments life extesion possibility. It's necessary to remark, that life time according of IEC Vocabulary [6] is defined by the going object to the term-limiting state. Durability measures in the standards are connected with the time to going into this state. But durability measures in technical documentation for instruments what include to monitoring system is presented without any exact definition of limiting state. Methodology for working of life extension is discribed in the document ÌÅ 306.711-96"Life extension of NPP instrument and control system equipment what important to safety. General requirements to work procedure and consistence". This document was elaborated in the Ukrainian Scientific Technical Center of Nuclear and Radiation Safety.

The work has 6 stages .
1. elaboration "Program of definition of possibility of life extension";
2. analysis of technical state;
3. testing;
4. analysis of reliability using operating experience;
5. elaboration "Conslusion about results of possibility of life extension";
6. elaboration "Decision about life extension".

These results were used for example for life extension of radiation safety monitoring systems unit 1-4 Zaporozhye NPP, unit 1-3 Yuzhno-Ukrainsk NPP, unit 1 Hmelnitsky NPP .

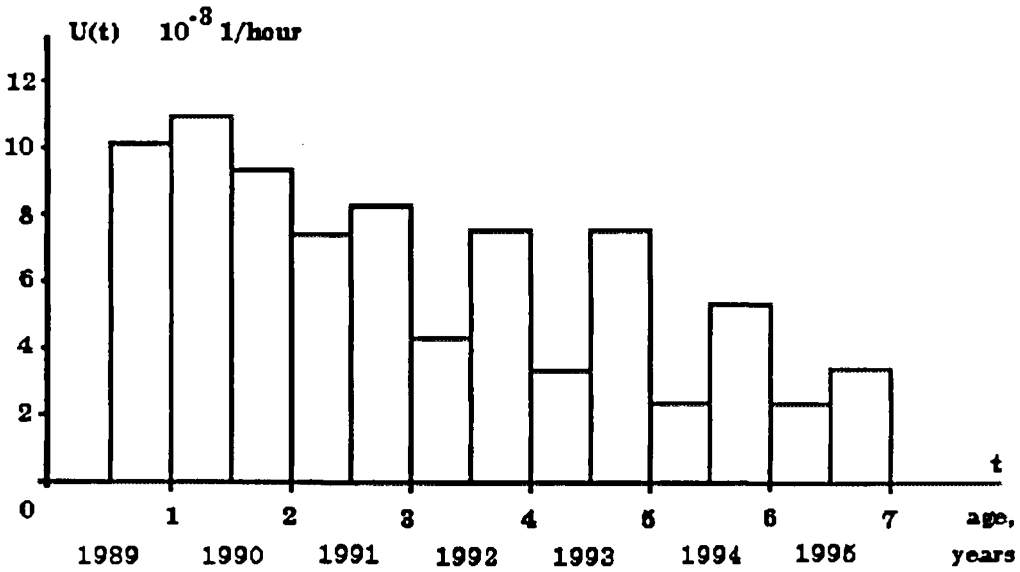
3. RELIABILITY OF THE SYSTEMS

Mathematical analysis of systems reliability was fulfilled by decomposition these systems on the set of functions (for example, measurment, annunciation, registration). The function are classified by complication into simple and composite. Simple functions are not decomposed to components; as rule, they consist in receiving information from one technological parameter and realise by one channel. Composite functions include some simple functions, what are jointed according to community of their purpose, constructive and other signs.

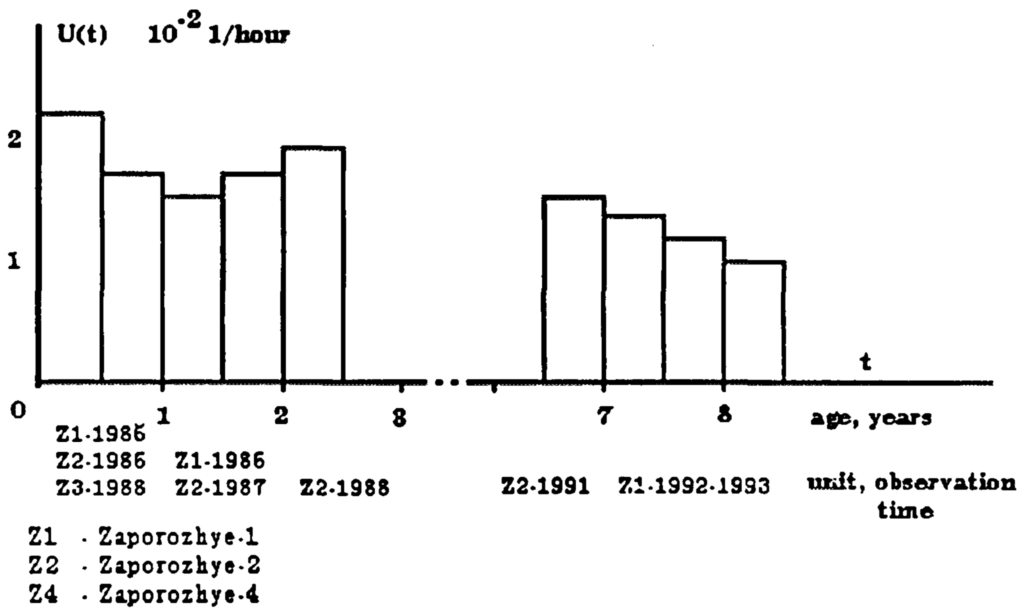
Definition of failure criterions of simple functions not causes any hardness. Definition of same criterions of composite functions usually is chosen from techological reasons. In the most cases, failure of composite function is event, when definite number or definite sets of simple function is faulted.

Reliability measures of simple functions of radiation safety monitoring system, simple and composite functions of information computer systems are shown at fig. 6.

RELATIONSHIP BETWEEN SUMMARY FAILURE INTENSITY AND TIME



a. Radiation safety monitoring system ÀÊÐÀ-03 (Yuzhno-Ukrainsk -3)



b. Information computer complex "Complex-Titan 2" components

Fig.5

RELIABILITY MEASURES OF DEVICES WHAT INCLUDE IN UNIT INFORMATION COMPUTER SYSTEM "COMPLEX- TITAN 2"

Name of device	Type	Number of devices	Operating time, 10^3, h	Number of failures	MTBF, h
Input subcomplex:	ÊÑÎ Ì-64				
Input analog device	ÁÃÐ	3440	55300	971	57000
Input discrete device	ÌÂÂ	1200	19300	252	77000
Commutator and primary processor	ÑÑÎ-Ê (central part)	160	10300	2708	3800
Concentrator	CÑÎ-Ó	24	1540	906	1700
Computer complex:	CM-2M				
Processor	A131	32	626	198	3200
Internal memory	A211	64	1252	88	14000
External memory	A322	32	626	382	1700
Personnel terminal:	ÐÏÒ-02				
Processor	À135	24	178	70	2500
Keyboard	À513	24	178	24	7400
Display	À543	48	356	71	5000

Fig.6

Evaluation of functions reliability fulfilled with acception of following circumstances:
- all failures of components included malfunctions (short-term operating violations what eliminated by automatic or manual restart without repairing) were calculated;
- term of disconnection of redundand devices for maintenance was calculated;
- repairing personnel are working during 8 hours per day.

The goals of evaluation of systems reliability:
- comparation with measures, what was written in technical documentation and standards;
- elaboration of requirements to reliability to modernized monitoring system, what will replace instead existing systems (This modernization proposed to 1997-2002 at the most of Ukrainian units VVER-1000).

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Session 2
Experiences with Monitoring and Diagnosis Systems

SESSION 2

EXPERIENCES WITH MONITORING AND DIAGNOSIS SYSTEMS

Chairpersons: Mr. M. DeVerno, Canada
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CONDITION MONITORING OF ROTORMACHINERY IN NUCLEAR POWER PLANTS

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ABSTRACT

Due to safety and economical reasons diagnostic and monitoring systems are of growing interest in nuclear power plants and other complex industrial productions. Key components of NPP's are rotating machineries of the primary and secondary loops like PWR main coolant pumps, BWR recirculation pumps, turbines, fresh water pumps and feed water pumps. Diagnostic systems are requested which detect, diagnose and localize faulty operation conditions at an early stage in order to prevent severe failures and to enable predictive and condition oriented maintenance.

The knowledge of characteristical machine signatures and their time dependent behavior are the basis of efficient condition monitoring of rotating machines. The performance of reference measurements are of importance for fault detection during operation by trend settings. The comparison with thresholds given by norms and standards is only a small section of available possibilities. Therefore, for each machinery own thresholds should be determined using statistical time values, spectra comparison, cepstrum analysis and correlation analysis for source localization corresponding to certain machine operation conditions.

1. Introduction

In order to optimize fault specific thresholds for diagnostic patterns of vibration and acceleration signals at rotating machines, failure simulations at different test benches are performed at the Institute of Nuclear Engineering and Nondestructive Testing (IKPH) of the University of Hannover for:

- touch simulation in turbo machines,
- investigations of rolling element and journal bearings,
- centrifugal pump supervision, and
- influences of cavitation.

The obtained signatures serve as base to determine machine specific signatures for trend setting of rotating machinery in power plants as:

- steam turbines (e.g. 1400 MW turbine KWG, 780 MW turbine KWM, 850 MW turbine KWH, 350 MW turbine KWO, 100 MW turbine HKWH),
- centrifugal water pumps (e.g. fresh water pumps KWG, fresh water pumps KW-Staudinger)
- nain coolant pumps of PWR (KWG, KKE, KKB), recirculation pumps of BWR (KKK, KGB)
- feed water pumps (e.g. main feed water pumps KWH)
- fan arrangements (e.g. mill fans HKH, fresh air fans HKH, exhaust fans KWM)
- steam security valves (e.g. HDU-KWH, HDU-KW-Rostock)

and industrial applications and production line as well as:

- oil pumps in terminals and refinery (PETROBRAS)
- paper mills (CHAMPION)
- gas pipeline arrangements (BEB gear valves, BEB turbine flow meters).

2. DATA ACQUISITION AND DATA PROCESSING

To the fulfillment of the demands on comprehensive vibration analysis, an aimed instrumentation of the unit to be supervised is compel whereby displacement, velocity and acceleration pick-ups are used. Often the already installed machine's instrumentation is capable to determine faulty operation conditions by suitable analysis and diagnostic techniques as:

- *time domain analysis* by statistical time values and their trend setting,
- *spectrum analysis* to determine machine specific signatures by magnitude and phase relation,
- *correlation analysis* to evaluate common information of different vibration signals for source localization, and
- *cepstrum analysis* to quantify periodical information of spectral data.

Applied are stationary and portable analysis systems, with sampling rates up to 800 kHz. The modular structure of the software permits the calculation of statistical time values (like standard deviation, crest-factor, kurtosis-factor, form-factor, etc.), the spectral density functions (auto/cross-power-spectral-density, transfer function, coherence, etc.), and cepstral values. Several graphical units are implemented for trend setting, the comparison of actual vibration signatures with references and thresholds. All software moduls can be used interactively as well as stand alone systems, operating automatically for alarm condition monitoring [1]. The structure of data processing and data acquisition is presented in figure 1.

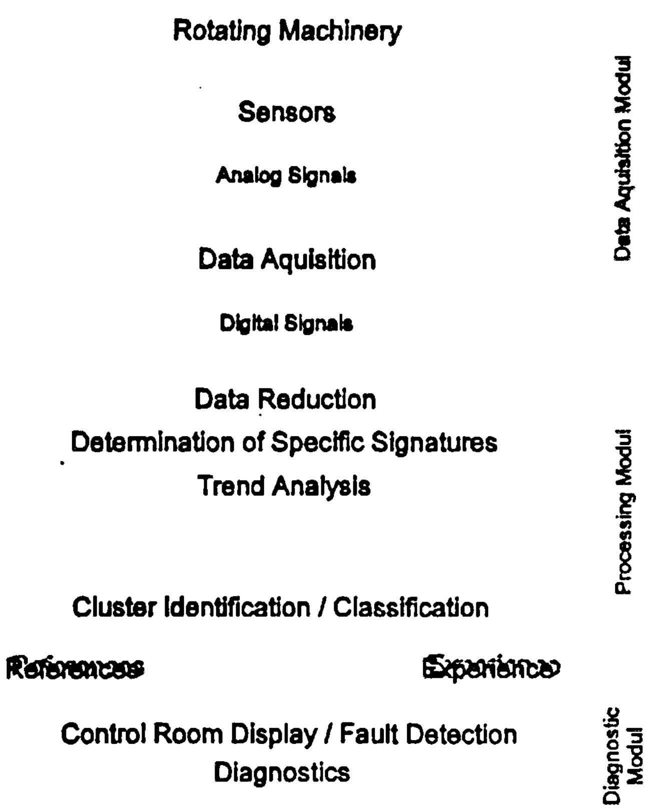

Fig.1: Flowchart of Data Processing and Acquisition

Case studies of fault detection at NPP turbines, feed water pumps, and electrical drive units using a portable multichannel vibration measuring system are presented in this paper. The influence of different faulty operation conditions to the characteristical values in time and frequency domain are described as well as trend settings and comparative measurements between similar machine arrangements. The discussion of practical operating experiences with the on-line condition monitoring systems ASMAS for PWR main coolant pumps is one of the main topics of the paper. The PC-based system uses the signals from electronic pump rotation speed tachometers to generate sampling signals synchronously to the pumps rotating speed. By use of this technique it is possible to measure those frequency components of the pump vibration which are correlated to the pumps revolutions (unbalance, rotation sound with harmonics) very exactly in frequency domain as well as averaging of signals in time domain to reduce stochastical signal components due to mechanical friction and electrical noise.

3. TIME DOMAIN ANALYSIS OF VIBRATION AND ACCELERATION SIGNALS

State of technology in vibration monitoring of rotating machines is related to the calculation of standard deviations and/or maximum values and their comparison with thresholds given by norms and standards, as e.g. fixed in VDI guideline 2056 /2059. The description of the vibrational behavior of rotors is often done by using fixed in VDI guideline 2056 /2059. The description of the vibrational behavior of rotors is often done by using the orbit of displacement. The point on the orbit where the maximum displacement occurs does not necessary coincide with the points where two under 90° fixed probe signals are at their maximum values. Using accelerometers fixed by 90° at the journal bearings of electrical drive units in combination with a computerized system for data processing, it becomes possible to determine by double integration of the acceleration signals the absolute displacement.

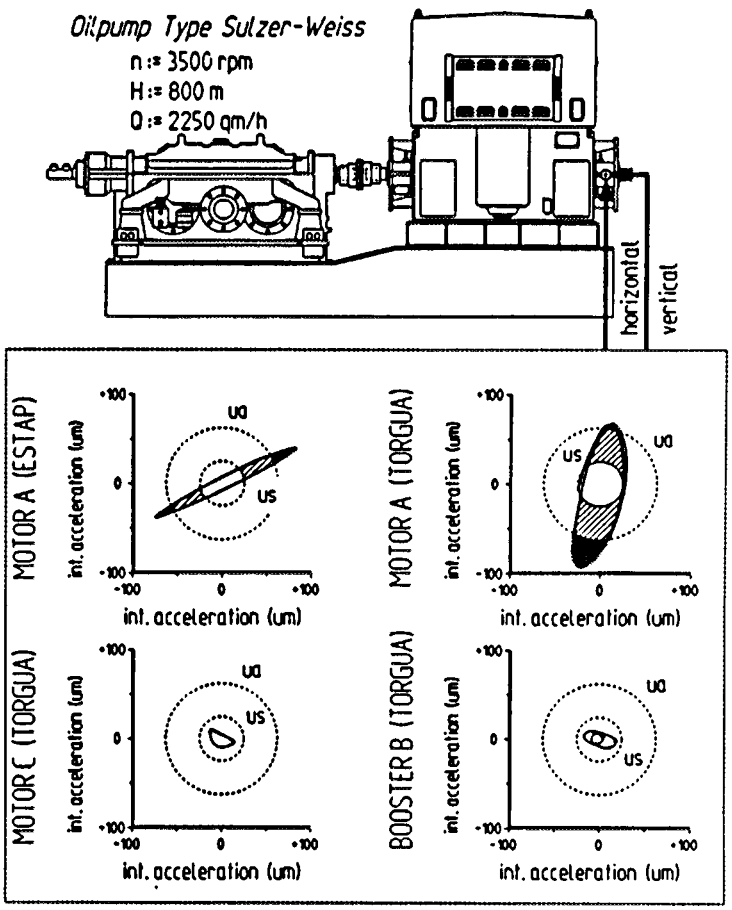

Fig.2: Orbits at different Motor Drives

Comparing several drive units a classification of the vibrational behavior is obtained, as shown in figure 2 at the example of electrical motors of main oil and booster pumps in pipeline systems. Corresponding to the thresholds given by VDI the limits of unsatisfactory (us) and unacceptable (ua) operation conditions are marked. In all cases as main source of excitation the unbalance becomes visible as one circle per revolution. By determining the orbits, additionally the direction of the main vibration amplitudes can be detected. As visible in the case of motor A at ESTAP the threshold of unacceptance is crossed at 45° presenting higher absolute values as could be determined by using the single detector signals. The motor unit of booster B (TORGUA) shows orbits with double loops per one revolution. The source of excitation which is of higher frequency than the unbalance itself can not be assigned only by visual impression of the orbit. Therefore, spectral analysis are required [2].

The use of modular multi channel supervision systems permit the application for small machinery as the electrical drives described above, but rather at complex turbo machines. Figure 3 presents orbits of the rotor from a 350 MW steam turbine during start-up and operation, measured with relative displacement pick-ups at the bearing blocks. Unfortunately operating conditions during start-up could be recognized by the on-line presenting of orbits, countermeasures in the machines operating conditions can be directly initiated by the control staff.

Through the simultaneous sampling of all displacement signals, the points of equal shaft rotating angle can be connected, giving hints to the absolute displacement of the turbine rotor, instabilities due to misalignment or oilwhirl/oilwhip, and superimposed structure resonances. The described steam turbine shows after maintenance higher signatures of unbalance excitation at the high pressure (HP) bearing block. During start-up additionally instabilities occur. Also here the source of excitation cannot be determined in time domain. Spectra analysis prove oil instabilities at about 50% of the rotating frequency, which are in resonance with pressure fluctuations of the steam regulation values for certain operation conditions, proved by correlation analysis between pressure transducers and the vibration signals.

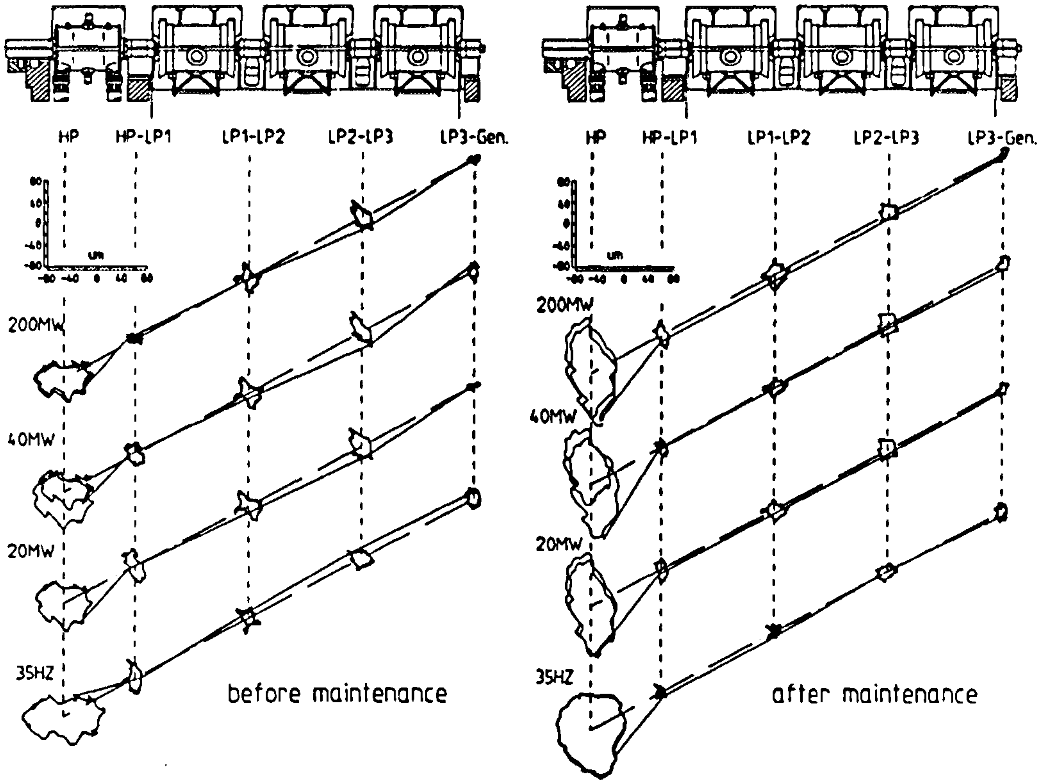

Fig.3: Orbits of Turbine Rotor for different Operation Conditions

To the premature determination of faults and damages of single machine components, the trend setting of certain statistical time values of the vibration signals suits itself. So the initiating and growing of defects in rolling element bearings of pumps and drive units [3] are clearly detected by using variance and kurtosis-factor as presented in figure 4 and figure 5. While the variance could be looked at as integrated value of vibration intensities the kurtosis factor emphasizes high frequent shock pulse excitations as they occur in case of local faults, when the rolling elements path the defected area of the raceways.

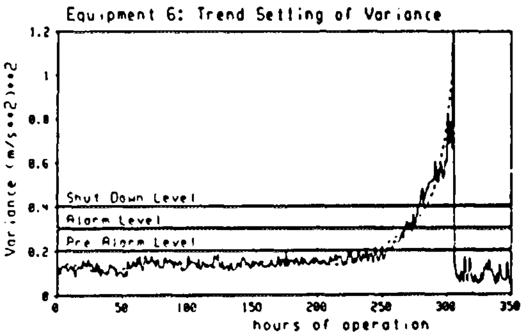

Fig.4: Variance of Acceleration

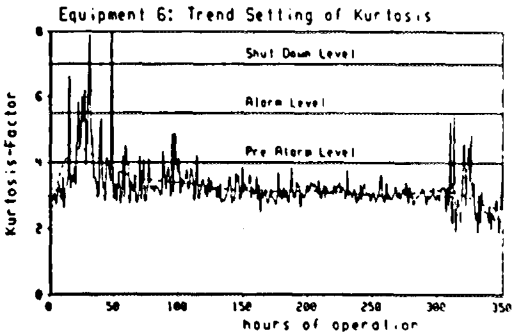

Fig.5: Kurtosis of Acceleration

In case of figure 5 the increased amplitudes of kurtosis within the first 100 hours of operation are related to the run-in time of the bearing, where the surface roughness due to the tooling process excites high frequent shock excitations. After 100 hours of operation the smoothening process is terminated, the kurtosis decrease to values of three, characterizing a statistical distributed vibration signal. After about 250 hours the variance starts to increase exponentially, crossing the alarm levels. The change of the faulty bearing after only 310 hours of operation reduce the vibration intensity to the initial value, the kurtosis is characterizing shock pulse excitations due to the run-in operation conditions. By these trend setting several failures could be determined in their early stage at fan arrangements in power plants, electrical drive units of fresh water pumps and gearings.

To the improvement of efficiency at turbo machines the air gaps of the stuffing boxes as well as the sealing of the runner and guide blades are diminished in spite of the therewith increased possibility of touching due to thermal bending of the rotor or casing deformation. Especially critical phases of touching are the start-up and shut-down conditions or increased gradients of load changes. The detection of touching in turbo machinery using accelerometer signals in dependence of relevant operating conditions is, therefore, both for the manufacturers and the operator of turbo machinery, of current importance.

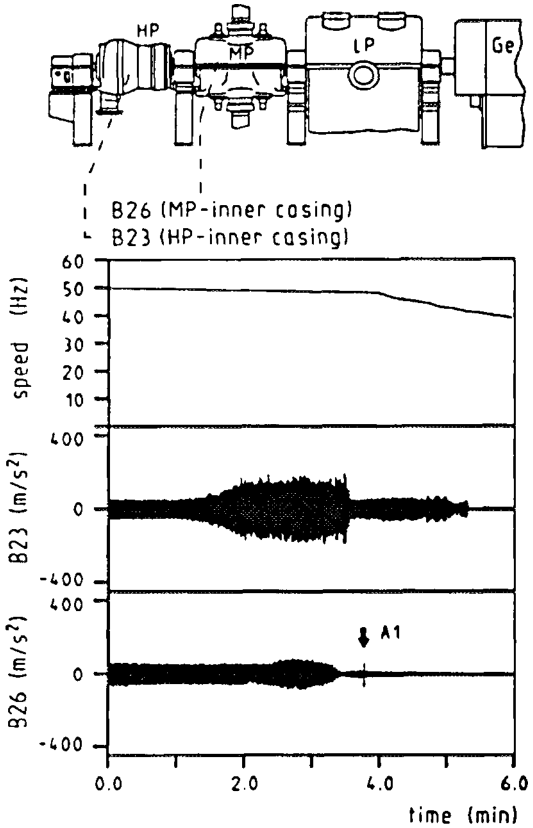

Fig.6: Signatures of Touching in Turbines

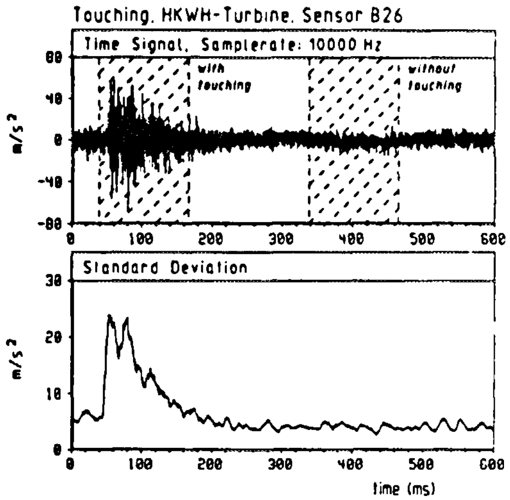

Fig.7: Signatures of Touching in Time Domain

Therefore, investigations should prove the applicability of acceleration measurements at the casing of steam turbines for determination of touching, the localization of the components in contact by correlation of different acceleration signals, and by statistical evaluation of the inherent operating condition to provide them.

Concerning here to transient high frequent excitation processes which rise up often only by some shaft revolutions, certain demands to the data acquisition and processing unit are required [4]. Figure 6 presents one typical short time shock excitation due to touching blade sealing and casing in the middle pressure part (MP) of a 100 MW steam turbine during shut down. Reducing the rotational speed, the acceleration signals show increased level of acceleration due to additional turbulence of steam flow, reduced in the moment of closing the steam regulation valves. After the valves at the MP-part are closed, a shock excitation (marked in the figure by A1) occurs, which after only 100 ms, corresponding to about 10 shaft rotations, drops down to the initial vibration level (figure 7). The force of the touching event is described by the gradient and absolute values of the standard deviation, which allows also to separate normal changes in operation conditions (e.g. high frequent acceleration due to operating steam and regulation valves) and the sources of touching.

4. SPECTRAL ANALYSIS OF VIBRATION AND ACCELERATION SIGNALS

By time domain analysis, as described before, the integral signature of the information in certain vibration signals is obtained within the sampled frequency range. The single frequency components contained in the time signals cannot be determined by amplitude and phase relations. For the presented example at the electrical drive units and turbine rotor, the unbalance excitation could be determined by using displacement signals, while the higher frequent as well as the lower frequent vibrational components could not be fixed, neither in their frequency nor amplitude. This can result through the calculation of the auto-power-spectral-density (APSD), assigning all information contained in the vibration signals of its respective frequency with accompanying intensity.

Figure 8 presents the APSD of acceleration at the housing of the main feed water pump in a 850 MW power plant for different operation conditions. The actual feed water pump from KSB consists of a high speed four stage main pump and a lower speed two stage pre-pump, connected by means of a right spur gearing. At nominal load the required power consumption is about 21 MW, placed at disposal by a double flow steam turbine. The load conditions are adjusted by changing the rotational speed of the driving turbine.

After maintenance of the steam turbine for power generation increasing the plants efficiency (from 800 MW to about 860 MW), the load of the feed water pump had to be modified too, leading to increased vibration levels of standard deviation, measured by the installed pump supervision system.

Therefore, additional vibration measurements were carried out to determine the source of excitation. The APSD's presented in figure 8 show the acceleration signatures at the main pump up to frequency

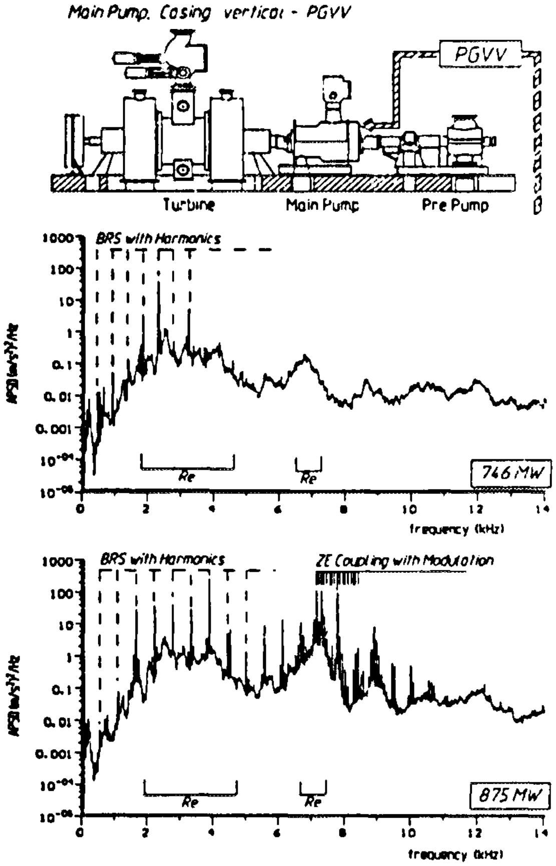

Fig.8: Vibration Signatures of a Feed Water Pump

components of 14 kHz for 746 MW electrical power, with main excitation sources of the blades rotation sound and harmonics as narrow banded information (BRS - number of blades x rotating frequency), superimposed by broad banded system resonances.

After changing the load to 875 MW the rotating frequency of the feed water pump has to increase, recognized by the postponement of the narrow banded excitations of the speed related BRS with harmonics. In addition appear at frequency range from 6 to 10 kHz narrow banded speed related acceleration components with speed modulations. Those are to be assigned to the coupling between main pump and gear transmission, which is operating in resonance.

This is not the only cause of the increased overall vibration level as be proved by the APSD's in figure 9, presenting the low frequent information of acceleration up to 100 Hz. The spectrum for generator powers of 746 MW and 875 MW are applied whereby in the upper part of the figure linear magnitude scaling and in the lower one logarithmic scaling is used.

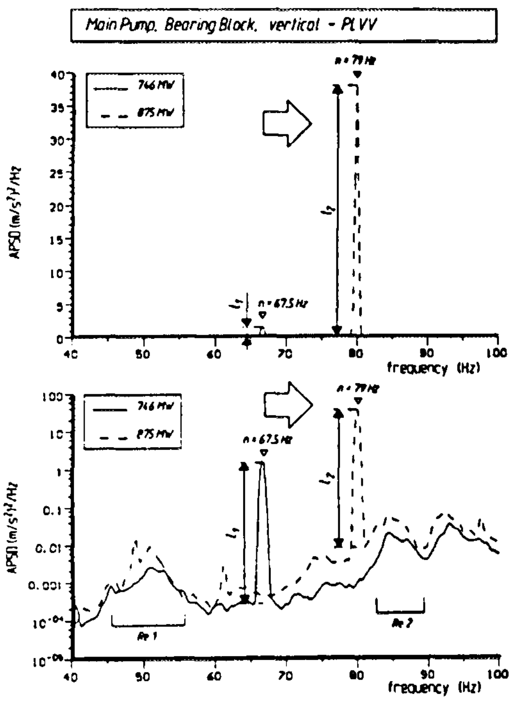

Fig.9: Low Frequent Vibration Signatures

In both cases, the unbalance excitation is to be recognized at frequencies of 67,5 Hz and 79 Hz, clearly. In addition the logarithmic spectra show two system resonances (marked with Re1, Re2), which can be assigned through estimated calculation of resonances of the concrete foundation.

In exclusive view of the linear spectra is noticeable that the magnitude of the speed related component at generator power of 875 MW is determined to 37 $(m/s^2)^2/Hz$, about 20 times the value of magnitude in APSD for generator loads of 746 MW. Through the inclusion of logarithmic spectra on the hand it becomes clear, that the amplitude of the rotation related component did not strongly increase by additional unbalance excitation, due to the fact that the marked length l_1 and l_2 are quite identical. Actually the increased vibration level concerns to superimposed unbalance excitation and structure resonances due to the incrc̣ased rotational machine's speed.

5. Cepstral Analysis

For automatical data acquisition and condition monitoring by multi channel vibration measurements, the amount of vibration data has to be reduced. Changes of operation, faulty conditions, and damages of rotating components become often visible by amplitude and/or frequency modulation near the speed related characteristical frequencies of the concerning machine part. Sidebands with distance of the rotating speed occur, which can be observed integral by calculation of the cepstral magnitudes, summarizing all periodical components appearing in a spectrum in only one peak [5].

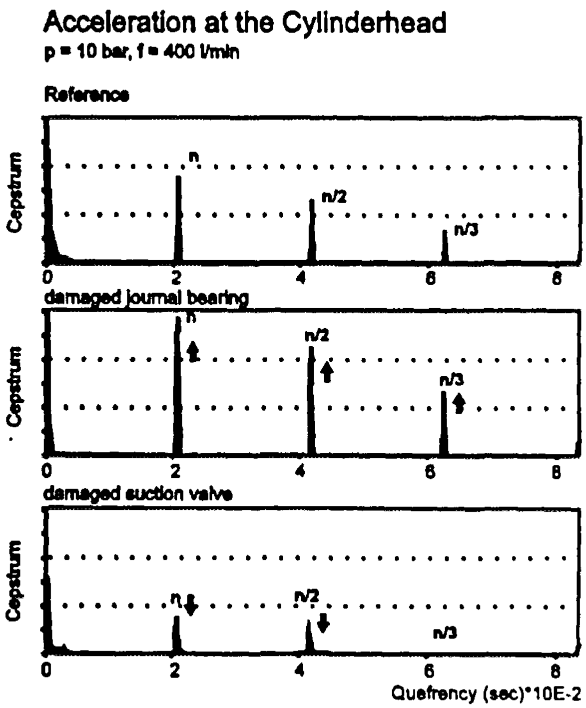

Fig.10: Cepstral Signatures at Piston Compressors

Figure 10 shows the cepstral magnitudes of acceleration at the cylinder head of a piston compressor for reference operation without defects, defected journal bearings, and damaged cylinder head gasket. In case of the increased bearing clearance in coincide with worst lubrication, additional speed related vibration components are excited with modulations. Therefore, the accompanying cepstrum magnitudes in the middle part of figure 10 show increase at the corresponding quefrency of rotation (n) and its subrahmonics (n/2, n/3).

If faults occur, which excite additional broad banded or stochastical vibrations, like the damaged cylinder head gasket, the speed related components of vibration are damped, the peaks at the rotation quefrency with rahmonics decrease. Therewith the cepstrum analysis offers the possibility to separate different failure sources and provide the possibility of data reduction for automatical alarm monitoring.

6. Correlation Analysis

The coherence function is used for determination of common information in different vibration signals. Examplarily shown in figure 11, where in the upper part two vibration time signals measured at a feed water pump are drawn, which show visually no similarities or common information. The left part presents the noisy displacement signal of a relative displacement pick-up inside the bearing block of the driving turbine with mainly low frequent speed related excitations. On the right hand side the acceleration signal on the bearing block shows mainly high frequent excitations, certain frequency components cannot be determined.

The lower left part of figure 11 presents the coherence function of both signals, where as common signal information the rotation frequency with harmonics and the blade rotation sound of the main feed pump is obtained (BRS). If all periodical information included in the coherence is supposed to be presented integral, the so-called hocerence can be used. With its aid, the result is the summary of all periodical components of coherence in one point, similarly to the calculation of cepstral magnitudes in the case of spectra. As become visible in the lower left part of figure 11 the hocerence includes only the speed related rahmonics of quefrency as common information for both signals. Therewith a further remedy arises to data reduction and the achievement of significant failure specific information as descriptive value of operation condition.

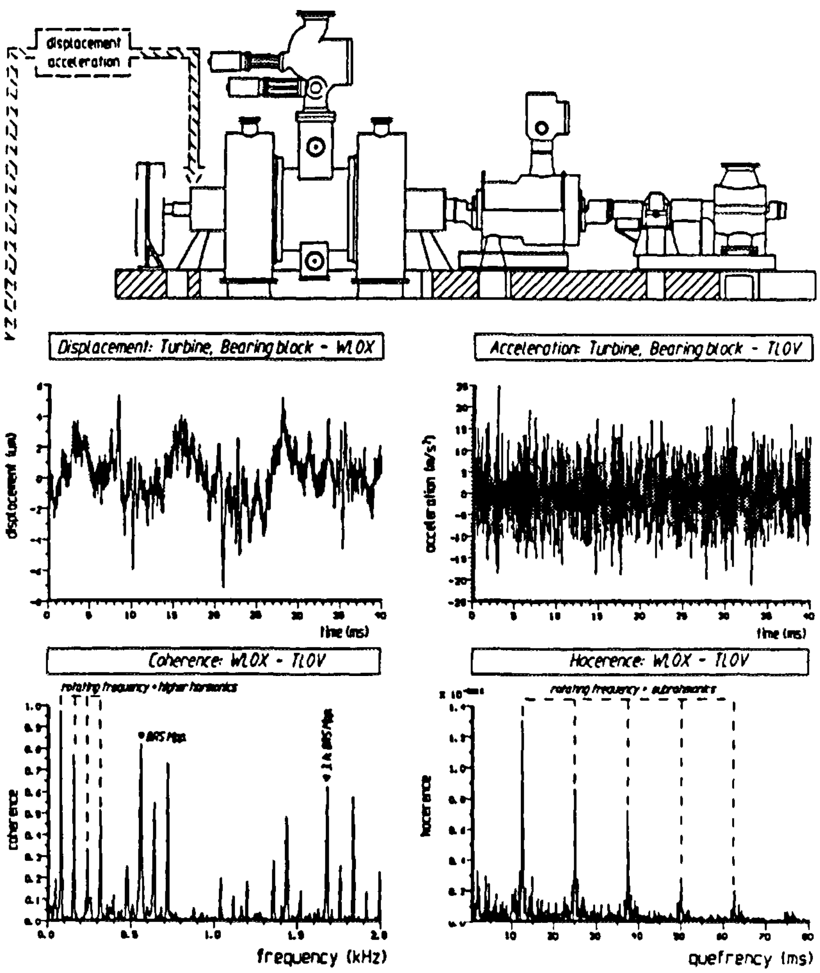

Fig.11: Coherence Analysis at Feed Water Pumps

Based on the above presented statistical values and function in time and frequency domain, vectors are defined. By algorithm of pattern recognition these vectors are compared with references, describing the failure source and its dimension [6].

The example of the PWR main coolant pump supervision system ASMAS should demonstrate the practical application of successfully implemented automatical supervision systems.

7. ON-LINE CONDITION MONITORING SYSTEM ASMAS

The main circulation pumps are key components of nuclear power plants with pressurized water reactors, because the availability of the main circulation pumps has a direct influence on the availability and electrical output of the entire plant. Shaft cracks, defect bearings or problematic unbalance of the main coolant pumps have occurred in pressurized water reactors [7,8,9,10].

For early failure detection and in order to avoid shaft ruptures or other severe problems of the main circulation pumps, manually operated and/or automated vibration control systems have been developed for on-line degradation surveillance of the reactor main coolant pumps [9,11,12,13,14]. The presented on-line automatic vibration control system ASMAS was developed for early failure detection of pumps in operation by FORTEC

GmbH, BSV GbR, IKPH Uni Hannover, and the nuclear power plant Grohnde (KWG). Actually it is operating successfully in three german 1300 MW_{el} NPP's as Grohnde (KWG), Emsland (KKE), and Brokdorf (KBR).

7.1. System Design

The general design of the system is illustrated in figure 12. The input signals from 4 (or more) main coolant pumps, MCP's, are generated by relative displacement between shaft and pump housing in x and y direction. Other signal sources are the absolute displacements of the pump housing, or the absolute and relative displacements of the primary circuit supervision system KÜS. Scanned by a PC controlled multiplexer, the input signals have a fixed predefined high pass filter of 1 Hz and a variable low pass filter to avoid the aliasing effect. The sample frequency is generated by a variable pulse-multiplier triggered by tachometer signal of each pump at one pulse per revolution. The analog digital conversion is done by using this revolution speed synchronous sample frequency in a 4-channel ADC sequentially for each pump, which allows later time averaging.

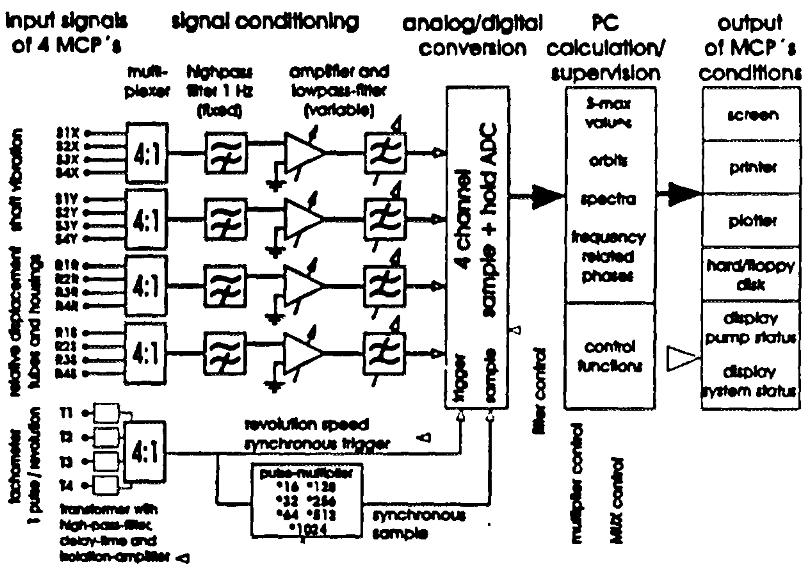

Fig.12: Structure of Hardware (ASMAS)

The automatical vibration control system ASMAS is able to perform three essential tasks, as there are the **monitoring** and **documentation** of all measured signals and results of analysis in time and frequency domain, by **status checks** of fixed thresholds the vibrational behavior of the MCP's is monitored. The features of automatical trend setting can be used for failure diagnostics, prognosis of developing incidents and for planned predictive maintenance of the main coolant pumps. Shaft cracks and other degradations as coupling misalignment, runner wheel cracks or bearing and sealing defects, which effect the vibrational behavior, can be detected in a very early stage by periodically checking independent warning and alarm thresholds. Dependent on the fixed thresholds and the vibrational behavior of the pumps the time averaged values of s_{max}, the amplitudes of 1[st] to 4[th] harmonics of rotation, as well as the frequency and phase related vibration vectors of these components are stored normally once a week. Crossing the pre-alarm level the results are stored once a day, in case of alarm the circle of storage is reduced to one hour.

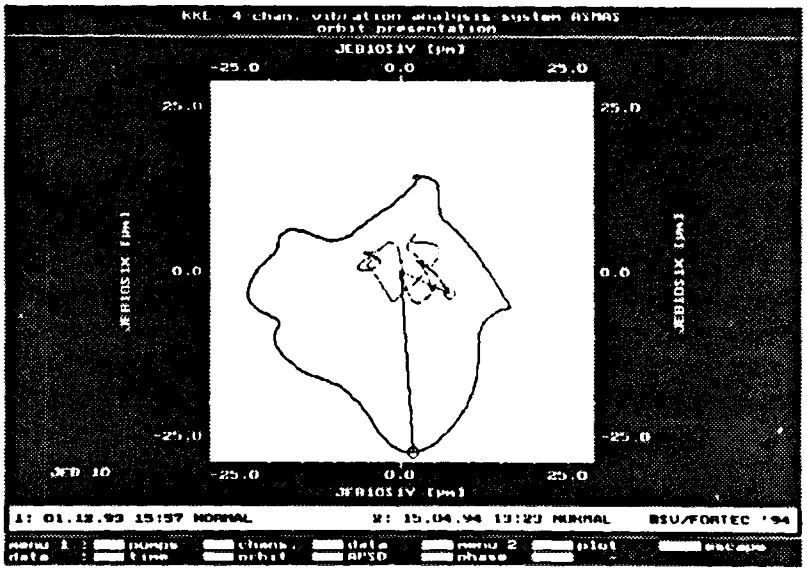

Fig.13: Orbits of Pump No.1 PWR Emsland (ASMAS)

7.1. Operating Experience

After a two days outage and the replacement of a sealing at pump no.1 significant changes of the vibrational behavior of one main coolant pump were detected in the NPP Emsland (KKE). After the outage a completely changed orbit (figure 13) was measured. The time signals decreased and the corresponding s_{max}-value was much lower than before, as well. Furthermore, changes of auto power spectral densities in frequency domain were detected (figure 14). Especially the amplitude of the first harmonic of rotation sound dropped from 17,9 μm to 0,97 μm in x-direction and from 17,4 μm to 4,6 μm in y-direction. The drop of the shaft vibration, especially at the first harmonic of rotation sound, was clearly detected in measurement no.34 after the restart of the pump and automatically caused an alarm due to the violation of predefined thresholds.

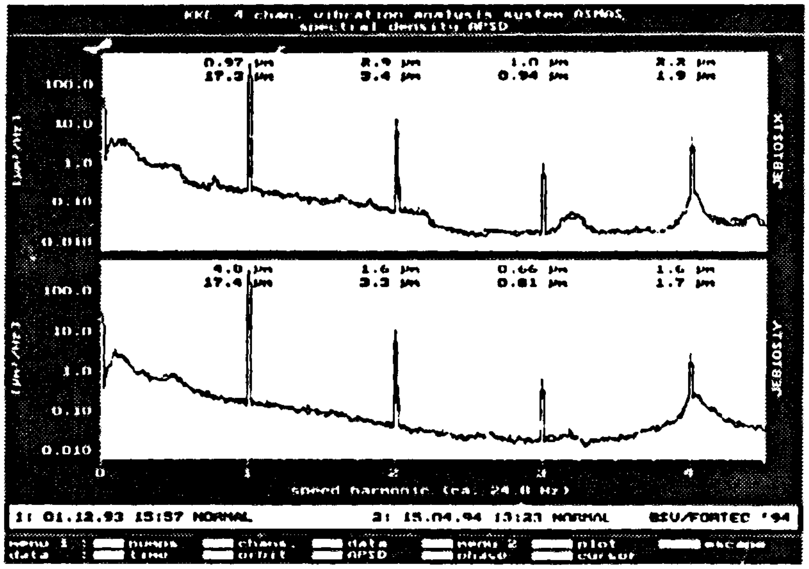

Fig.14: APSD's of Displacement of Pump No.1 PWR Emsland (ASMAS)

The trend analysis of the magnitudes of the first harmonic of rotation speed of pump no.1 in figure 15 indicates a more or less stable vibration condition after the outage. Obviously there was no indication of continuous increase or decease of the vibration levels. This leads to the conclusion that there was no slowly developed failure but a permanent one with no changing influence to the levels after the outage.

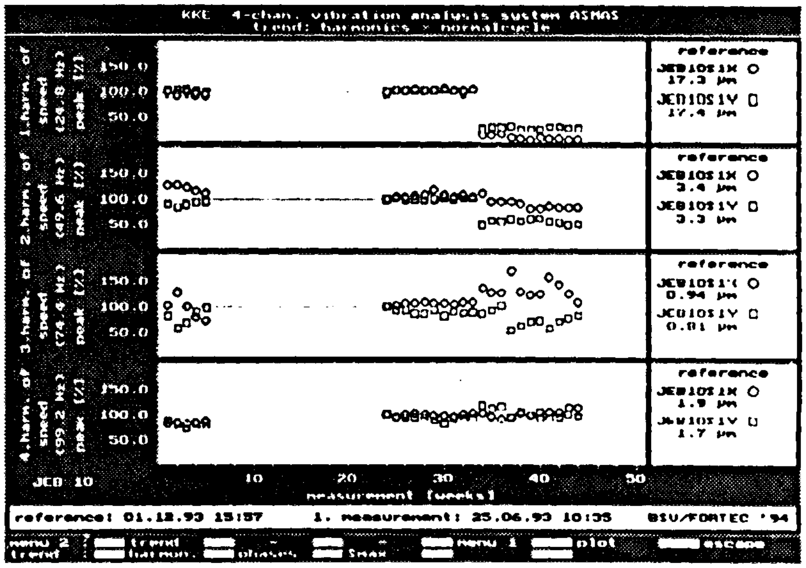

Fig.15: Trend Analysis of Magnitude of APSD Components (KKE)

To determine the source of changed vibrational behavior the relative displacement signals at the loop system were analyzed, additionally. Here could be stated that the amplitude level of vibration for the first harmonic of rotating frequency increased at the pump housing after start up, whereas the relative displacement between shaft and housing had decreased. At this time, the next regularly planned shut down of the NPP was close in time and the inspection of this pump was done again. During this inspection, the missing of balance elements was found out, which had not been remounted during the previous inspection. The balance elements could be replaced and after pump restart, the vibrational behavior of pump no.1 reached the normal levels again. This illustrates that the use of the automatic vibrational system ASMAS enables early failure detection and prevents severe damages of the components.

After operational tests, performed by the german technical inspection agencies, the potentiality and reliability of the system has been demonstrated during accumulated period of about nine years in operation. Based on the regarded experiences of manual and automatical operating condition monitoring systems in power plants also a permanent control system based on data evaluation of acceleration signals for touch control in main circulation pumps is implemented at the NPP Obrigheim (KWO).

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EXTERNAL VIBRATIONS MEASUREMENT OF REACTOR COMPONENTS

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SYNOPSIS

The paper outlines the use of External Vibration Monitoring for remote vibration assessment of internal reactor components. The main features of the technique are illustrated by a detailed examination of the specific application to the problem of Heysham 2 Fuel Plug Unit monitoring.

1. INTRODUCTION

The internal structures of nuclear reactors are subject to a variety of excitation mechanisms, resulting from such sources as coolant flow and acoustic noise generation by circulating pumps. In some cases it is necessary to monitor reactor components, to ensure that any significant responses to such excitation will be detected at an early stage prior to the onset of any damage. In general, the most effective method of monitoring dynamic behaviour is to attach measurement transducers directly to the structure involved. In the case of reactor components this is not always possible, because of the restrictions imposed by the operating environment. Particular difficulties are caused by high temperatures, high radiation levels and difficulty of access to structures within the reactor pressure vessel. In some cases it has been necessary to develop alternative monitoring strategies based on remote vibration measurement.

External Vibration Monitoring (EVM) relies on the existence of suitable pathways between components subject to vibration, and external locations. Transmission of energy along such pathways enables remote monitoring of structures which can not be measured directly. In reactor structures it is generally the case that multiple pathways will exist between each monitoring site and any particular vibrating component, and thus each monitoring site will receive inputs from many different sources. This complexity has meant that great care must be taken in assessing the usefulness of the techniques for any particular application, but nevertheless it has proved to be a very successful monitoring tool in nuclear plant.

This paper describes in detail, the EVM system which has been installed at Heysham 2 Power Station to monitor the vibration characteristics of the fuel plug units. In addition, other applications are discussed in less detail and the general problems associated with EVM are considered.

2. THE REQUIREMENT FOR EVM ON HEYSHAM 2

Heysham 2 Power Station contains two Advanced Gas Cooled Reactors (AGR), each with a design output capacity of 660 MW (electrical). A general schematic of the reactors is shown in Figure 1. Each reactor core contains 332 fuel stringers comprised of eight fuel elements and a plug unit. The plug unit serves to seal the fuel elements into the core, to provide a radiological and thermal shield and to regulate the flow of the coolant CO_2 gas through the fuel. The flow regulation, which is used as the means of controlling the coolant outlet temperature, is achieved by means of a variable area gag/orifice unit, shown schematically in Figure 2. The design of this assembly is identical to that employed on the two earlier AGR's at Hinkley Point B and Hunterston and consists of a tapered centre body which can be moved up and down in a fixed orifice thereby altering the coolant flow area.

During the early commissioning tests at Hinkley Point B, the gags on a small number of plug units exhibited a violent instability which caused severe damage to the plug unit components. The ensuing investigations revealed that the coolant flow in the annular gap between the centre body and the orifice produced both steady and fluctuating forces. The steady force biases the gag against the orifice and can be considered as stabilising forces, whereas the fluctuating force tends to de-stabilise the gag. Under certain circumstances, the fluctuating force exceeds the steady force and instability occurs. Design modifications were implemented, which produced gag stability over all design operating conditions. The modifications were incorporated into the designs of Hinkley Point B and Hunterston Power Stations and all four reactors have now operated incident free for a number of years.

The modifications produced a gag design which did not exhibit any gross instability in assemblies which were built within the design tolerances and which were also subject to normal operation. However, the design is not stable in an absolute sense and there are two factors which must be considered. The first is that the stability is dependent on the eccentricity of the gag, defined as the displacement between the centre of the gag and the centre of the orifice. The test work demonstrated that minor instability might occur when the eccentricity reached a value of 1.45m, and that gross instability could occur if the eccentricity exceeded 2.0mm. The design tolerances for the gag components are such that a maximum eccentricity of 0.78mm can result from manufacture, and thus there is a substantial margin against instability at start of life. The second factor concerns low amplitude flow induced motions, which may produce wear between the gag fins and orifice thus increasing the eccentricity.

Following the experience at Hinkley Point B, it was recognised that the problem of potential gag instability would have to be considered for the Heysham 2 Power Station design. An analysis of the operational data from Hinkley Point B and Hunterston was carried out with the conclusion that the probability of occurrence of an unstable gag was less than 1×10^{-4} per reactor year. Even with this very low predicted probability for the occurrence of gag instability, the decision was taken to install a monitoring system which would be capable of detecting an unstable gag should it occur.

3. THE PRINCIPLE OF GAG INSTABILITY DETECTION

The EVM system installed at Heysham 2 relies on the mechanical transmission of vibration signals to an accelerometer mounted externally on the plug unit closure external to the pressure vessel. The detection of impacts, which occur if the gag collides with the orifice, is then achieved by measuring their effect on the amplitude distribution of the signal. The normal vibration signal of a plug unit, Figure 3 (a), can be characterised by a stationary narrow band random signal with an amplitude distribution which is very closely Gaussian, Figure 3 (b). The effect of impacts on such a signal is to introduce a relatively small number of high amplitude peaks, Figure 3 (c), which have a consequent effect on the amplitude distribution, Figure 3 (d). The presence of such peaks can be determined by examining the statistical properties of the amplitude distribution.

In general two measures are used to assess a signal for the presence of impacts. The first of these, referred to as exceedence measurement, involves sampling the signal to build up the amplitude distribution and then comparing the prevalence of samples in the extremes of the sampled distribution with that which would be expected for a Gaussion distribution. In the case of the Heysham 2 EVM system, the comparison is based on the number of samples lying more than four standard deviations from the mean. The probability of individual samples being more than four standard deviations from the mean is very low and this requires the acquisition of a large number of samples to ensure the statistical significance of the result.

The second approach is to measure the kurtosis of the signal as defined by:-

$$k = \frac{1}{N\sigma^4} \Sigma_{i=1}^{N} (x_i - \bar{x})^4$$

where k = kurtosis, σ = standard deviation, N = number of data points, x = mean value of signal, x = instantaneous value of signal.

This parameter, also known as the normalised fourth statistical moment, is proportional to the fourth power of the instantaneous deviation of the signal from the mean and is therefore very sensitive to large amplitude excursions. Because the kurtosis is a normalised parameter, its value is independent of rms value of the signal.

For a signal characterised by a true Gaussian amplitude distribution the value is exactly 3, whereas if the signal contains some impacting component the value of kurtosis is greater than 3.

When using kurtosis or exceedence measurements for impact detection it is important to consider both the number of samples required and the period over which they are taken. The number of samples required is dictated by statistical considerations as discussed above, while the sample period is dictated by the signal parameters. In particular, it is important that the sample time should be long enough to contain a reasonable number of impacts.

4. SYSTEM TESTING

Because of the difficulties associated with the interpretation of EVM signals, the decision was taken to undertake a test to demonstrate that the EVM system could detect an unstable gag under normal operating conditions. An additional benefit to be gained from such tests was that it would permit the data sampling parameters and alarm levels to be set, on the basis of directly relevant test information.

To produce an impacting gag under controlled conditions, a specially instrumented plug unit with a modified gag centre body was attached a complete fuel stringer. The modifications to the gag involved the machining of a taper onto part of the gag fins, so that when the gas was moved over this portion of its travel the eccentricity of the gag in the orifice would increase, to the extent that instability would result. The instrumentation included displacement transducers local to the gag assembly, which could be used to both monitor for the onset of instability and assess its severity by estimating the gag velocity at impact. The fuel stringer was loaded into the reactor for testing during the unfuelled engineering tests.

The tests were carried out with the gas flows in the reactor adjusted to be similar to those which would be experienced during normal full load operation. During the test the gag was gradually moved towards the closed position, from the fully open stable position, and all of the instrumentation was carefully monitored for signs of instability. Once instability of the gag had been induced, further movements were very restricted because of rapid increases in the severity of the vibration.

The EVM system had also been employed to a large extent during all of the station commissioning tests. This work had identified a number of other potential sources of impacting type signals (ie signals with high kurtosis and exceedence values) which were not related to the instability of concern and which, on examination, had been identified as being benign in nature. From an operational point of view, it is important that any system which produces alarms to the operator should not do so in a spurious manner. It was thus important to devise a reliable method of discriminating between those impacting signals caused by an unstable gag and those originating elsewhere.

Analysis of the frequency spectra associated with the impacting signals revealed that, in those cases where the impacting was not associated with an unstable gag, only the higher frequency components were enhanced during the impacts. Conversely, for the unstable gag test, the impacting resulted in an increase in energy across the whole frequency spectrum. This led to the obvious conclusion that filtering of the signal prior to analysis would provide a suitable method of discrimination. The success of this approach can be seen in Figure 4, which shows the effect of filtering on the kurtosis value for both the unstable gag test and a typical impacting signal originating from another source. Included on Figure 4, for reference purposes, are plots showing the result obtained from unfiltered data simultaneous with the filtered data. The effect of filtering on the exceedence parameter is similar to that obtained for the kurtosis parameter.

Figure 5 illustrates the variation of the kurtosis parameter measured during the unstable gag test, using filtered data with an upper cut off of 1kHz. The sharp increase in the value of this parameter, at a gag position of just beyond five inches closed, corresponds to the onset of gag instability as measured by all of the instrumentation on the plug unit. Once again, the behaviour of the exceedence parameter shows a similar sharp increase at the onset of gag instability consistent with the kurtosis data.

In addition to the work outlined above, the test on the modified plug unit included an endurance run of twelve hours, with the gag positioned so that is was unstable and producing a signal easily detectable by the EVM system. Subsequent removal and inspection of the modified gag assembly confirmed that no damage had been caused to any of the components during the test. This test demonstrated that, at the level of vibration detectable by the EVM system, quite prolonged activity could be tolerated without incurring any damage to the plug unit. This is an important aspect in relation to the specification for the EVM system, in that it gives an indication of the scan time required for the system.

5. SYSTEM IMPLEMENTATION

The EVM system installed at Heysham 2 is shown schematically in figure 6. Piezoelectric accelerometers are mounted on the plug unit closures of each of the 332 fuel channels. The charge signals generated by these transducers are led individually to a marshalling cubicle at the side of the reactor pressure vessel. Switching devices are used to select signals in groups of fourteen which are routed, via charge amplifiers, to a remote analysis facility.

The prime requirement of the analysis equipment is the measurement of the exceedence and kurtosis parameters. This is achieved by means of a purpose built digital signal capture system, which samples two input channels simultaneously at a sample rate of 10kHz per channel. Data is sampled for 15 seconds on each plug unit and the analyser uses this data to construct an amplitude histogram. This histogram is subsequently used by the main control computer to calculate the kurtosis and exceedence parameters.

A secondary requirement of the system is to check the input signals for both signal and transducer faults. These checks include high/low checks on the signal rms value and high mains frequency pick up checks. The skewness of the amplitude distribution is also computed and this provides a useful indication of alarms being generated as a result of spurious electrical spikes.

Test signals, with known properties, are injected at the marshalling cubicle to provide an overall check of the switching and analysis functions. The system contains three parallel alarm output units, which are designed to fail-to-safety in the event of a power loss. The alarm cards will also go to the alarm state if they are not addressed by the control computer on a regular basis, thus providing an independent protection against processor faults.

The whole system is controlled by a small workstation computer which, in its present configuration, completes a scan of all plug units every two hours. The system operates continuously under automatic control, while the reactors are at power or while there are gas flows sufficient to cause the gag instability. The operation of the system can be interrupted by authorised persons to permit manual investigations of any alarms which might occur and it reverts to normal automatic operation if inadvertently left in this state.

Considering the low probability with which a gag instability is expected to occur and the high degree of reliability and self checking which is built into the EVM system, the overall probability of a gag becoming unstable and remaining undetected is considered to be insignificantly small.

6. OPERATIONAL EXPERIENCE

The full Heysham 2 EVM system was commissioned prior to the start of power raising and it was operated both in its normal automatic mode and under manual control, to fulfil specific commissioning requirements, during the whole raise to power sequence. Since reaching full power the system has continued to operate in automatic mode and no instances of genuine alarms have been monitored although there have been a small number of occasions where alarms have been raised where investigations have shown them to be related to external causes.

7. OTHER APPLICATIONS OF EVM

The system described in the preceding sections was designed and installed to fulfil a specific monitoring requirement, during the operating lifetime of the station. The necessity for the system had been identified sufficiently early in the construction and commissioning programme to allow testing to be carried out, which demonstrated the capacity of the system to meet the particular monitoring requirement. There are many other possible applications of such systems however, which are of a less well specified or of a temporary nature, and some of these are explored in subsequent sections.

7.1 Reactor Commissioning

The main use of EVM systems, in the experience of the authors, has been their use during reactor commissioning tests. The system described above was the development of a prototype system which was originally intended for commissioning purposes only. In addition, EVM was used extensively to measure fuel stringer vibrations during the commissioning of the Heysham 1 and Hartlepool reactors in the early 1980's.

The reason for the use of EVM systems during commissioning is to provide an insurance against some undesirable behaviour, not identified during the design stage, which may occur on either a systematic basis or on a small number of rogue components. At the time of commissioning Heysham 1, there was little experience of the use of EVM and the system employed covered only about 10% of channels. However, the system identified a potential vibration problem which gives a good illustration of the value of EVM.

The commissioning tests at Heysham 1 and Hartlepool were conducted in two stages. The first of these was an unfuelled engineering run during which the plug units were in the pressure vessel, but without any fuel attached. The second was a fuelled run, but with the reactor not in a critical condition.

During the unfuelled engineering run, the EVM system detected very large amplitude, almost pure sinusoidal signals on one of the channels with EVM instrumentation. A manual survey of the full core revealed that a small number of plug units were exhibiting the effect whilst the majority showed no untoward behaviour. A feature of the plug units used for the unfuelled engineering run, was that an orifice plate was attached to the bottom end, to produce a pressure drop equivalent to that which would normally be associated with the presence of fuel. There were two designs of orifice plate, representing two types of fuel stringer configuration, and it became apparent that the high vibration levels were associated with only one of these designs.

Full scale air rig tests were carried out and demonstrated that the cause of the whistle was a jet switching phenomenon associated with the interaction between the orifice plate and the leading edge of the neutron shield plug. This behaviour produced an acoustic tone which then interacted with the resonances of cavities within the plug unit to produce extremely high sound pressure levels. A further feature of the rig tests was that the behaviour was critically dependent on the precise alignment between the orifice and the neuton shield plug.

Although this example relates to components which were not intended for operational use it is important, because it highlights the limitations of rig tests during the design stage which are of necessity limited in scope. In this case the plug had been tested, in the configuration used for the unfuelled engineering run, without any problems being identified, and it was only by making a detailed investigation, with the knowledge that some effect existed, that the mechanism was elucidated.

7.2 Boiler Vibration Monitoring

During the early years of operation at Wylfa Power Station a vibration problem developed, which led to leaks in a number of boiler tubes on one of the two reactors. The investigation into the cause of this problem concluded that a flow induced tube response resulted in relative motion between the boiler tubes and their retaining clips, and produced consequential fretting damage. Engineering modifications were made to the boiler which altered the tube response characteristics and limited the possible motion at the tube/clip interface.

Following the implementation of these modifications, the rate of tube leaks reduced dramatically, but over the next few years the leak rate built up again. A new investigation programme was instigated which included an EVM system with the dual purpose of determining whether changes in vibration pattern were associated with the occurrence of boiler leaks, and as a long term vibration monitoring system.

The only access to the boilers for measurement is external to the pressure vessel, on either the superheater penetrations or on the economiser penetrations. Tests indicated that the background noise, associated with the flow of steam in the superheater penetrations, was too high to permit meaningful measurements to be made. The economiser penetrations, however, had relatively low flow noise associated with them and represented a possible site for EVM measurements.

A small number of vibration transducers were installed on the boiler tubes inside the pressure vessel, as a part of the overall investigation, and these were used to demonstrate that vibration signals originating in the boiler could be detected on the penetration. However, a significant part of the external signal was originating from other sources and, for the system to be useful, it was necessary to develop a technique of discriminating against this interference. Fortunately the design of the boilers, shown schematically in Figure 6, was of some assistance in this respect. The boiler platens fed from adjacent penetrations are interleaved in the boiler with good mechanical coupling between them. Thus any vibration signal generated at a particular location in the boiler should be transmitted equally well to both of the penetrations feeding that area. By measuring the vibration signals of adjacent penetrations simultaneously, and only considering that part of the signal which was coherent between the two, it was possible to eliminate a large portion of the background noise and leave a signal that was representative of the boiler vibration.

An EVM system, based on the analysis techniques outlined above, was installed at Wylfa and has now operated for several years. The data obtained from this system has demonstrated that the occurrence of leaks can not be related to any abnormal behaviour or operating conditions, and during its period operation no significant changes have been observed.

8. CONCLUDING REMARKS

The three examples sited above are all situations in which EVM has been applied successfully in a nuclear environment. These examples serve to illustrate some of the important features of applying the technique, and these are reiterated below.

When looking at specific problems, it is essential that a reasonable transmission path exists between the source of the vibration and the monitoring position. The transfer characteristics of this path must be assessed and other signal sources must be considered to ensure that the information obtained can be correctly interpreted.

Wherever possible, specific tests should be carried out to demonstrate the applicability of the technique.

If EVM is to be used in a nonspecific application, such as commissioning where there is no foreknowledge of the vibration characteristics of the components being monitored, it is essential to measure a large enough sample to be able to identify abnormal or undesirable behaviour. Careful consideration must then be given to specific testing, intended to identify the cause of such behaviour.

Finally, on those occasions when EVM has been applied successfully, it has proved a valuable method of component health monitoring in situations where measurements would have been otherwise impossible.

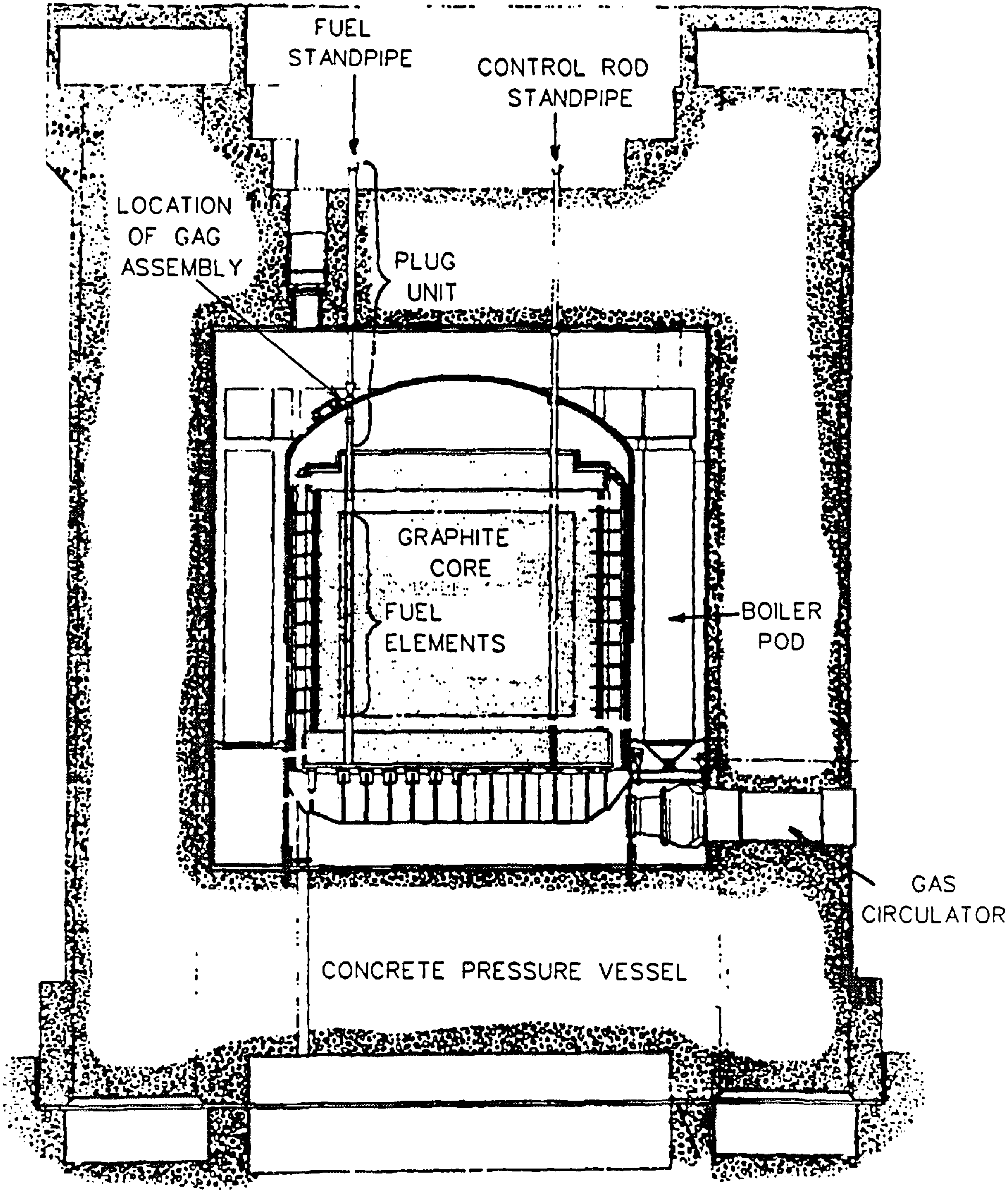

FIG.1 HEYSHAM 2 REACTOR GENERAL LAYOUT

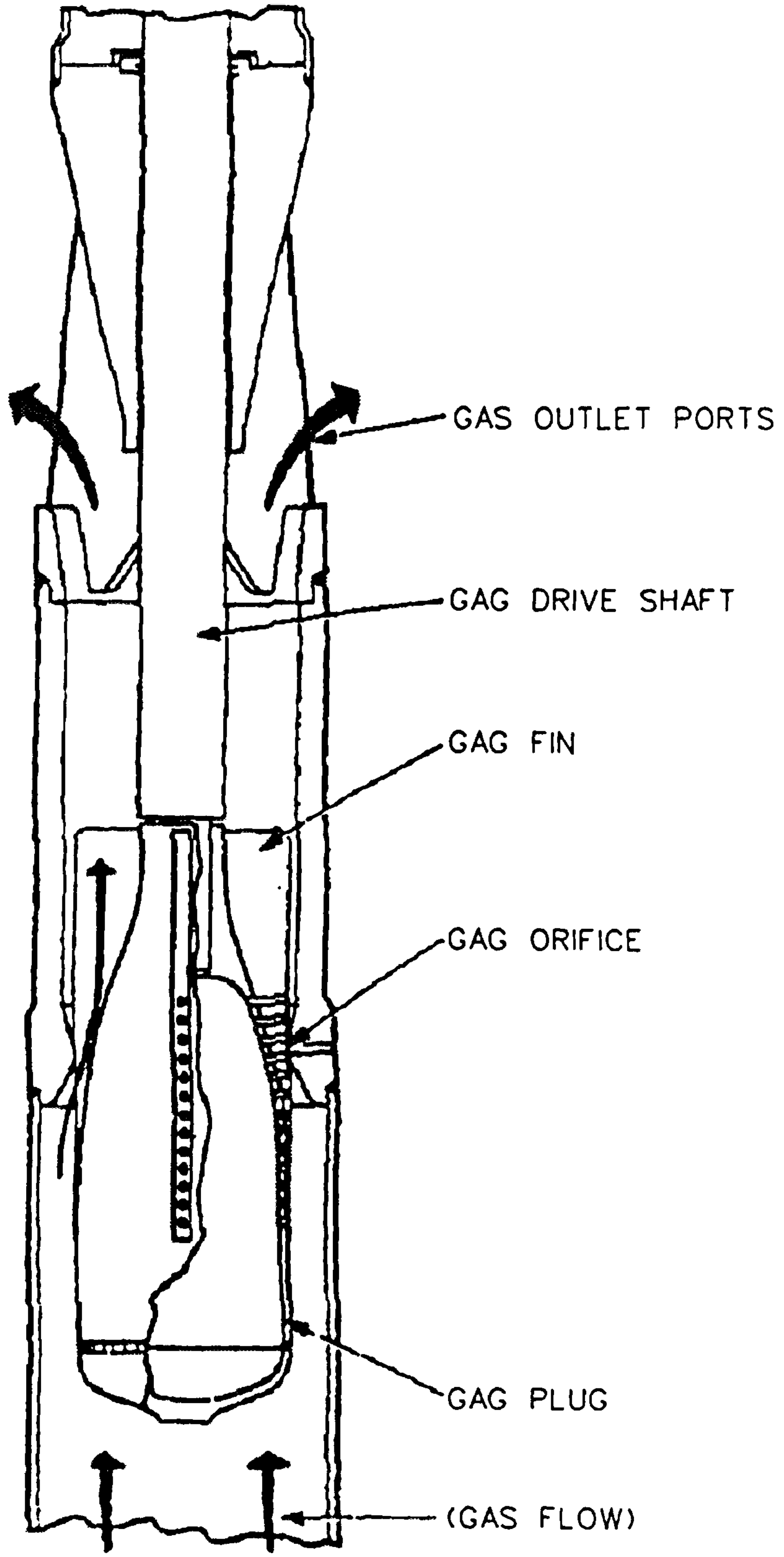

FIG.2 HEYSHAM 2 GAG / ORIFICE ASSEMBLY

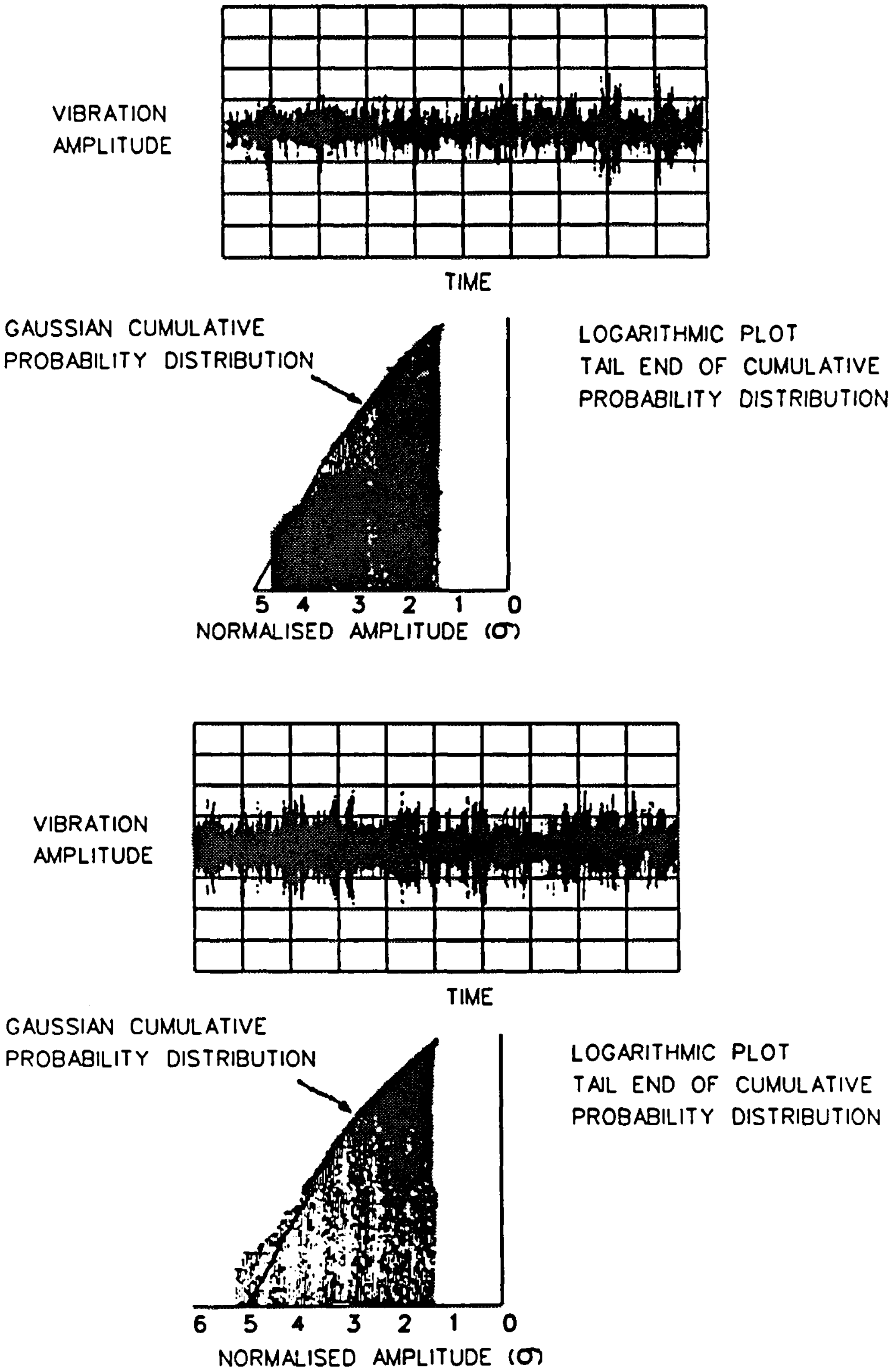

FIG.3 (a) Vibration Time History For Signal With No Impacting
(b) Logarithmic Amplitude Distribution Of (a)
(c) Vibration History For Signal With Impacting
(d) Logarithmic Amplitude Distribution Of (c)

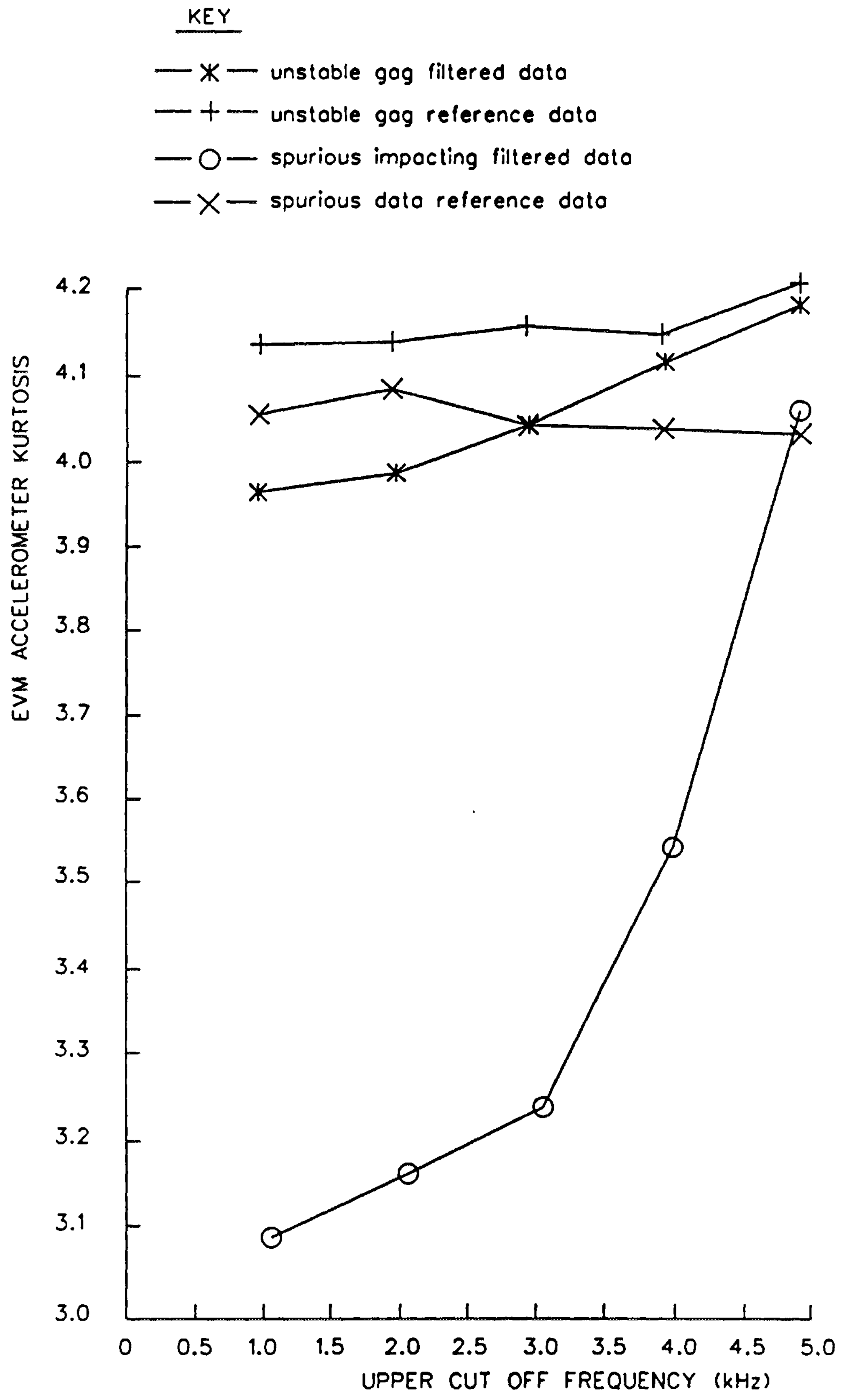

FIG.4 VARIATION OF KURTOSIS WITH FILTER BAND WIDTH FOR UNSTABLE GAG SIGNAL AND SPURIOUS IMPACTING SIGNAL

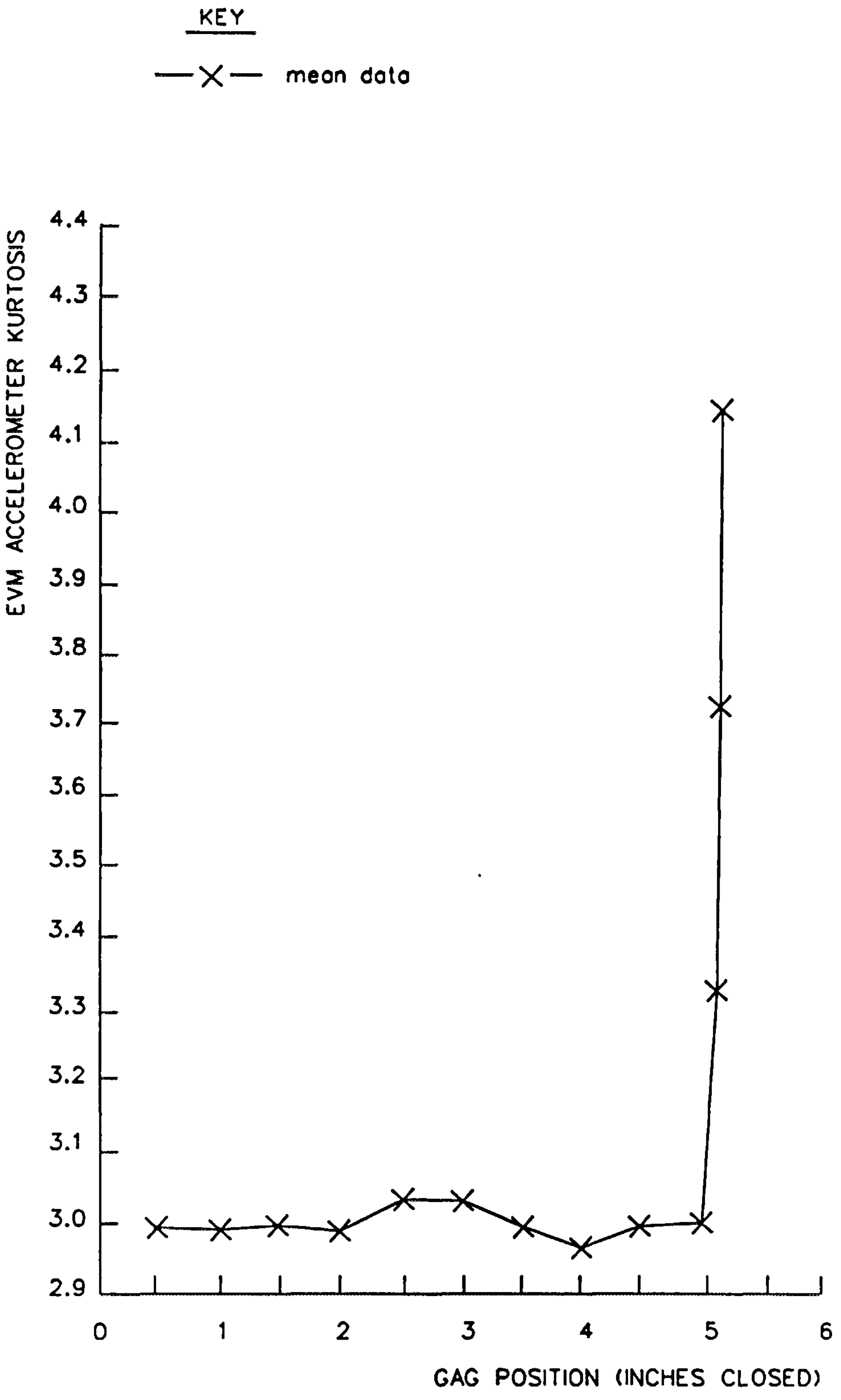

FIG.5 VARIATION OF EVM ACCELEROMETER KURTOSIS WITH GAG POSITION DURING UNSTABLE GAG TEST

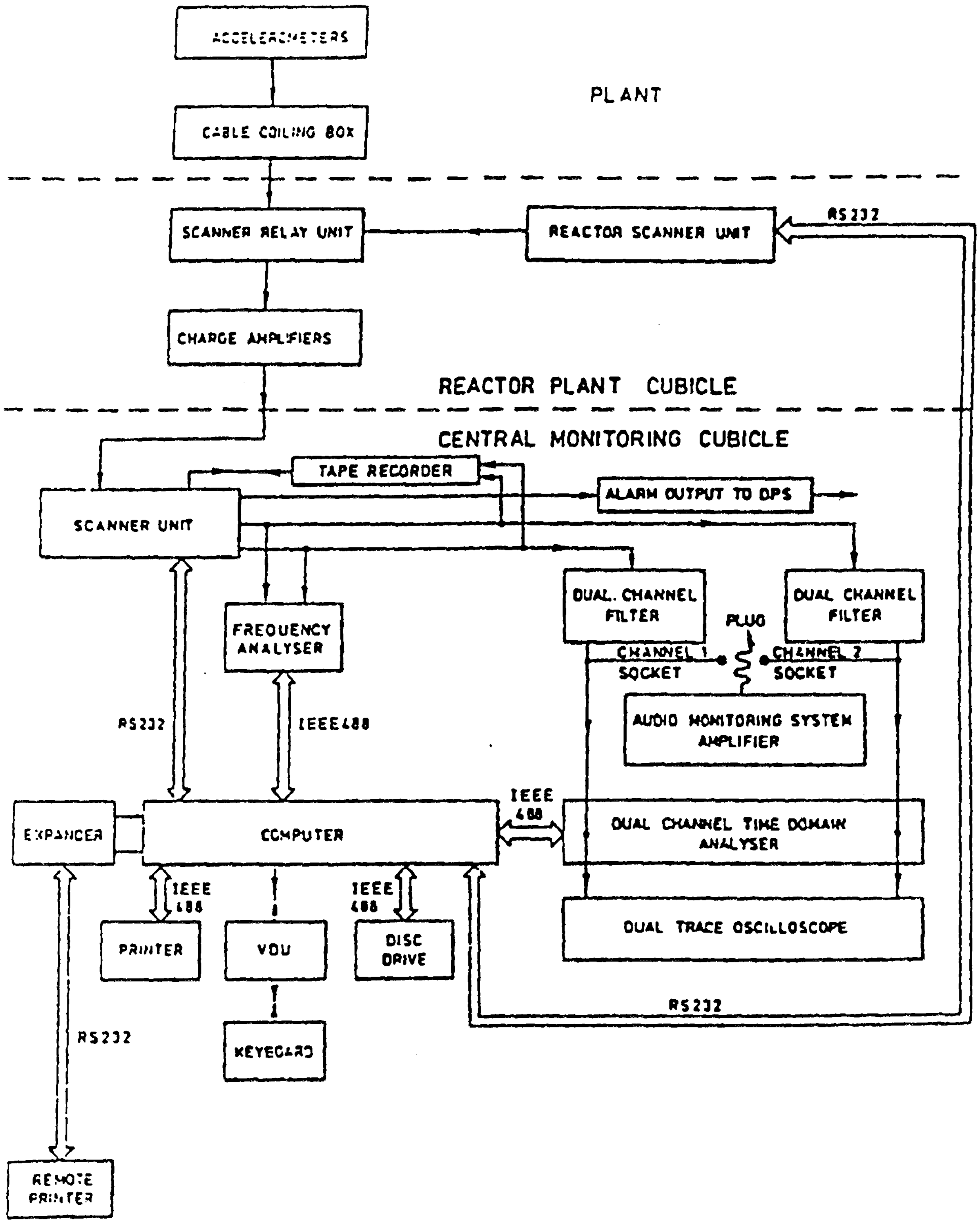

FIG.6 STANDARD VIBRATION MONITORING SYSTEM BLOCK DIAGRAM

XA9743565

PROPHYLACTIC AND THERMOVISION MEASUREMENTS OF ELECTRIC MACHINES AND EQUIPMENT

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ABSTRACT:

High-voltage measurements of generators, unit and service transformers and some significant motor drives used at a nuclear power plant are described in this paper. Thermovision measurements of electric machines and distribution systems are dealt with in the second part of the paper.
Power electric equipment represent one of the most significant components of a nuclear power plant. Turbine mechanical energy is converted into the electrical energy within these equipment. Power generated by generators is transformed by transformers so that it can achieve appropriate parameters for both the transmission over the distribution system and the power plant service power supply. The service power supply switchboards and cables provide power supply to motors and other consumers necessary for the nuclear power plant technological process. The whole complex of equipment has to be maintained in good technical condition.

It is necessary to make thermovision and prophylactic measurements to identify and verify the electric equipment technical condition. The mentioned measurements warn the operation staff in advance against both gradual deterioration of power connection contact resistances, i.e. power connections overheating, and the machine insulation systems condition deterioration. The operation staff try to prevent the electric equipment operation accidents by early removing the detected failures, thus, improving the nuclear safety.

In order to provide the above-mentioned activities a special prophylactic measurement group was established at the NPP Bohunice in 1983. The group specialists make following types of measurements:

1. Prophylactic measurements of electric machines.

1. 1. Prophylactics of 220 MW generators and 6 MW service power generators,
1. 2. Prophylactics of both unit and service transformers and VHV bushings,
1. 3. Prophylactics of major 6 kV motor drives.

2. Thermovision measurements of current connections

Measurements enumerated in paragraph 1 are made on disconnected electric machines during refuelling outages, thermovision measurements are made under reactor unit full operation conditions, i.e. on equipment energised to the rated level.

1.1. Prophylactics of 220 MW Generators and 6 MW Service Power Generators

A generator is disconnected from both encased conductors (in the points of bushings) routed to the respective unit transformer and connectors routed to the neutral point during measurements. The main generator stator winding must be dried up by means of pressure air so that water remaining in the winding can not distort measured values.

Phase-to-Earth Insulation Resistance Measurements

Measurements are made with the TETTEX HV-10 type 5430 megaohmmeter steplessly controllable up to 10 kV. Insulation resistance of a respective phase is measured against earth under voltage of 5 kV, the remaining phases being earthed. Measurements are made in function of time: readouts are taken after 15, 60 and 600 seconds. Polarisation indices p_{i1} and p_{i10} are calculated that equal to:

$$p_{i1} = R_{60} / R_{15} \qquad\qquad p_{i10} = R_{600} / R_{60} .$$

If polarisation index values exceed 1.3, the stator insulation condition is sufficient, if they range over 2.0, the condition is good. Polarisation index values depend on both moisture contents and pollution of the insulation system. The higher is the value, the drier is the insulation. The polarisation index is used for approximate review of the insulation condition. Subsequent measurements are only made if the winding insulation resistance equals to at least 700 MΩ.

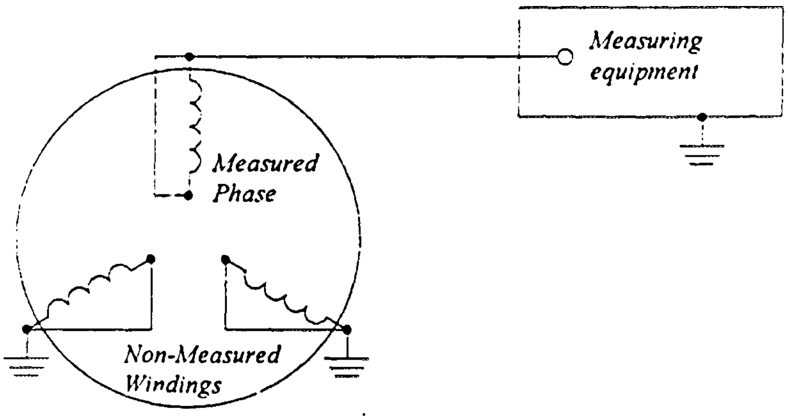

Fig. 1: Interconnection between a measured winding and the measuring equipment

Capacity and Loss Factor Measurements

The loss factor tg δ is defined as a ratio of active to reactive current. In case that measurements are made on an insulation material, it represents the extent to which electrical energy is converted into heat. Rise in the loss factor tg δ, as well as delta tg δ, is a generally accepted criterion of insulation material ageing. It is important to measure both loss factor and capacity against applied voltage if the ageing insulation material conductivity mechanism is being changed. Capacity C is measured in μF, loss factor tg δ is a dimensionless quantity.

Measurements are made with a semi-automatic measuring bridge TETTEX 2809, supplied from HV power sources TETTEX 5281 and 5287. Voltage levels of 3.1.4.7, 6.3, 7.9, 9.0.9.4, and 10.0 kV are applied to respective phases when measurements are made. Non-measured phases are earthed. Values of tg δ are compared within ranges of 0.2 - 0.5 Un, 0.4 - 0.6 Un and 0.2 - 0.4 Un.

Values of tg δ must not exceed 2 %. If a higher value has been measured, it indicates that the stator winding is a geing and getting wet.

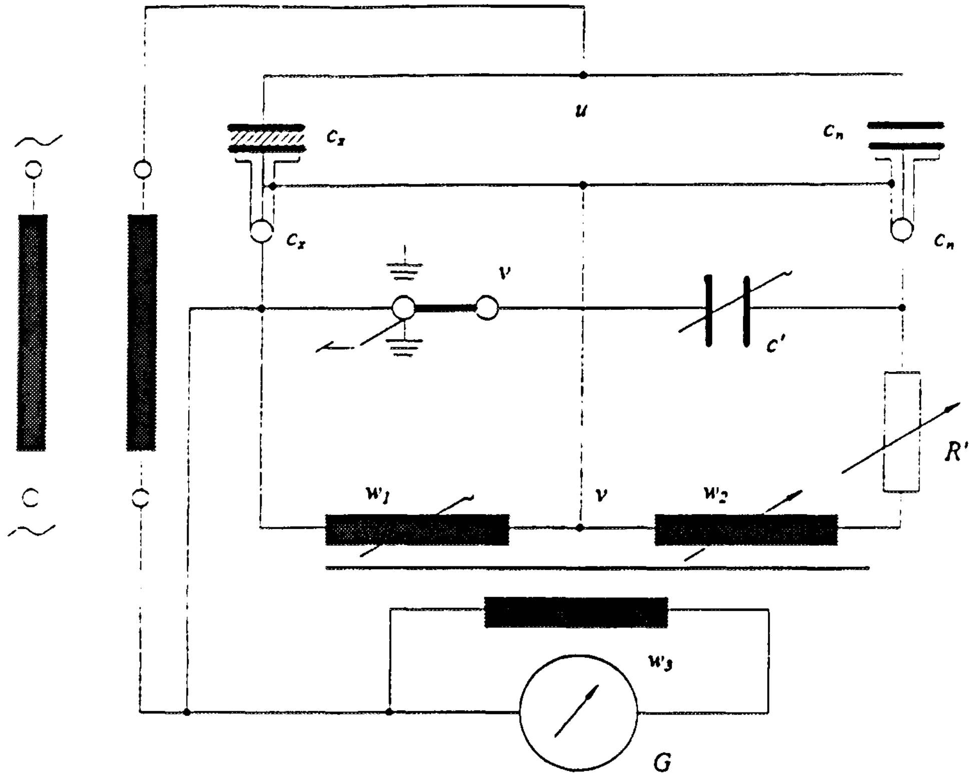

Fig. 2: Principial Wiring Diagram of C and tg δ Measurements Made by Means of a Measuring Bridge

Charging Current Measurements

Charging currents are measured with the BAUR PGK/45 DC power source. Measurements are made phase by phase, the non-measured phases being earthed. Charging current values are read out at voltage levels of 5, 8, 10, 12 and 15 kV in time periods of 60 and 300 seconds. R_x resistance is calculated out of measured values:

$$R_X = U / I_{300} .$$

High - Voltage Test

A high-voltage test is made following each generator major overhaul involving winding repairs. DC voltage of 41 kV is applied to each of the phases for 60 seconds.
Measurements of windings are made with the BAUR PGK/45 DC power source. The -15,75 kV generator bushings high-voltage tests are also made by means of the application of 65 kV DC voltage supplied from the PGK/1OO DC power source.

The mentioned measurements helped us to detect insufficient insulation condition of the NPP V 1 generator bushings. Insulation resistance must be always measured by means of 5 kV DC voltage prior to and following each high-voltage test.

1.2. Prophylactics of both Unit and Service Transformers and VHV Bushings

Oil represents an essential component of transformer insulation. The special prophylactic measurement group specialists have no chromatographic analysis equipment of their own available. That is why they co-operate with the Diagnostic Center Križovany in this field.

The transformer must be disconnected at both primary and secondary sides during measurements and its bushings must be cleaned up.

Winding Insulation Resistance Measurements

Insulation resistances of the windings are measured with the TETTEX HV-10 type 5430 megaohmmeter by means of 2.5 kV DC voltage application. Readouts are taken after 15 and 60 seconds. Polarisation indices are calculated out of the measured values in a way similar to the generator insulation resistance measurements. Following winding and support connection combinations are used for the measurements:

I.	VHV	:	HV		
II.	VHV	:	HV	+	S
III.	VHV	:	S		
IV.	HV	:	VHV		
V.	HV	:	VHV	+	S
VI.	HV	:	S		

Note: VHV - very-high-voltage side
HV - high-voltage side
S - Winding support

Capacity and Loss Factor Measurements

10 kV/50 Hz voltage is applied to different connection combinations as mentioned above. If the major overhaul takes place in winter, measurements must be done immediately following disconnecting the transformer from the grid, i.e. before the transformer temperature drops below 20° C, because the loss factor value is temperature-dependent.

Magnetising Current Measurements

Magnetising currents are measured with digital multimeters by means of 380 V 50 Hz AC voltage application. Windings of lower voltage are only measured on unit transformers, as the windings are wound over each other (HV, VHV).

If any higher-voltage winding displacement or short circuit, etc. occurred, this would always be transformed into the lower-voltage winding, too. Both VHV and HV sides are measured on the plant service transformers. Transformer taps No. 1, 9 and 19 are measured on the VHV side, whereas tap No. 9 is measured on the HV side.

Winding Ohmic Resistance Measurements

Measurements are made by means of the TETTEX 2285 computer system running under special transformer ohmic resistance measurement software.

The measurement system provides following measurement possibilities:

- single current source I = 1 - 50 A,
- two current sources for separate measurements, i.e two objects can be measured at a time,
- a couple of current sources connectedin parallel, current supply up to 100 A.

The measuring system measures either ambient temperature or oil temperature by measurement probes. Measured values are subsequently used for ohmic resistance correction in relation to selected reference temperature (20°C is the selected value). The measuring system provides remote switching over of plant service transformer taps.

Following the measuring system start up it takes the power source (or power sources) several seconds to supply the selected current to the winding. The ohmic resistance value should be stabilised. It is important to observe whether the value only drops or fluctuates, i.e. it can not be stabilised. The stable value is logged and next transformer tap of a higher number is switched over by the measuring system. All 19 taps of the plant service transformer are measured in this manner. The higher-voltage side is supplied with current of 100 A, the lower-voltage side with 50 A.

A trend line connecting measured value points must form a straight line in case of the NPP V 1 plant service transformers, whereas that of the NPP V 2 plant service transformers must form a parabola. The difference consists in different types of change-over switches. In case that some values are not located on the straight line or parabola or they fluctuate, a definite conclusion can be drawn that there is a defective current connection inside the transformer. Practice indicates it is just this type of measurements that gives the best idea of the transformer current connections condition. It has enabled early identification of severe failures inside transformers at both the NPP Bohunice and Dukovany several times.

400 kV (220 kV) bushings represent very important components of unit transformers. Their insulation resistance is measured by means of 2,5 kV voltage application between the measured point and the transformer frame. Besides, both their capacity and loss factor are also measured.

Capacity C_1, as well as loss factor tg δ_1, are measured by means of 10 kV voltage applied to the bushing outlet (top). The measuring cable is connected to the measured point of a bushing and the earthing cable is connected to the transformer frame. The measuring bridge is connectedin UST wiring scheme, i.e. VHV:HV.

Capacity C_2, as well as loss factor tg δ_2, are measured under the voltage of 2 kV after both voltage and measuring cables have been interchanged. The measuring bridge is connectedin GST wiring scheme, i.e. VHV:HV+S.

1.3. Prophylactics of major 6 kV motor drives

The scope of measurements has been extended nowadays to cover also some major motor drives at the NPP. Both 4.8 MW cooling water pump motor drives and 2.1 MW steam generator feedwater pump motor drives are included. Both motors are of the three-phase asynchronous type, their stators being connectedin Y or 2Y-connection. Unlike the cooling pump motor drives, neutrals of the feedwater pump motor drives Y-connection are not connected to terminal boxes. Thus, it is not possible to make measurements on each respective phase. Following motor drive parameters are measured:

- insulation condition - by means of 5 kV voltage application,
- capacity and loss factor at voltage levels of 2, 4, and 6 kV,
- partial discharges.

Insulation condition, capacity and loss factor are measured in the way described in paragraph 1a).

Partial Discharges Measurements

Insulation systems of electric machine stator windings are never perfectly homogenous. They contain lots of tiny cavities arisen during the machine manufacture and operation. The relative permittivity of gases inside the cavities is er times as low as that of the insulation material. This results in a fact that gases inside the cavities are subjected to er times higher gradient than the insulation material. Moreover, electric strength of an insulation material is higher than that of a gas. That is why breakdowns occur inside cavities at a voltage level much lower than the insulation material breakdown voltage. Discharges occurring inside the cavities are called partial discharges, as they do not span the whole distance between electrodes, but only a short section.

The TETTEX 9126 measuring device is available for partial discharge measurements. It is equipped with its own measuring, processing and recording device and an oscilloscope. The TETTEX 5287 and TETTEX 5281 control transformers are used as HV power sources. The wiring diagram is depicted in Figure 3. The coupling capacitor compensating the partial discharge power must be located as close to the measured machine as possible so as to eleminate the condenser - machine connection interfering effects as far as possible. The aim is to measure both the voltage level at which the discharges start to be displayed on the oscilloscope screen and capacity and current levels of the discharges. Measurements are made at selected voltage levels (e.g. 4, 5, 6 kV).

It is of high significance to eliminate interfering effects of the environment as far as possible during measurements. Following interfering effects are among the most dangerous ones: close located conductive objects without fixed potential, electromagnetic waves of radio transmitters, coupling capacitor. (wrong earthed), tips near both the measuring and HV cables connecting points.

The group specialists have only been making this type of measurements from less than two years. The measured values data bank is, therefore, not very large. Yet, the specialists unambiguously detected insufficient insulation conditions of four feedwater pump motor drives on the basis of both partial discharge and capacity and loss factor measurements.

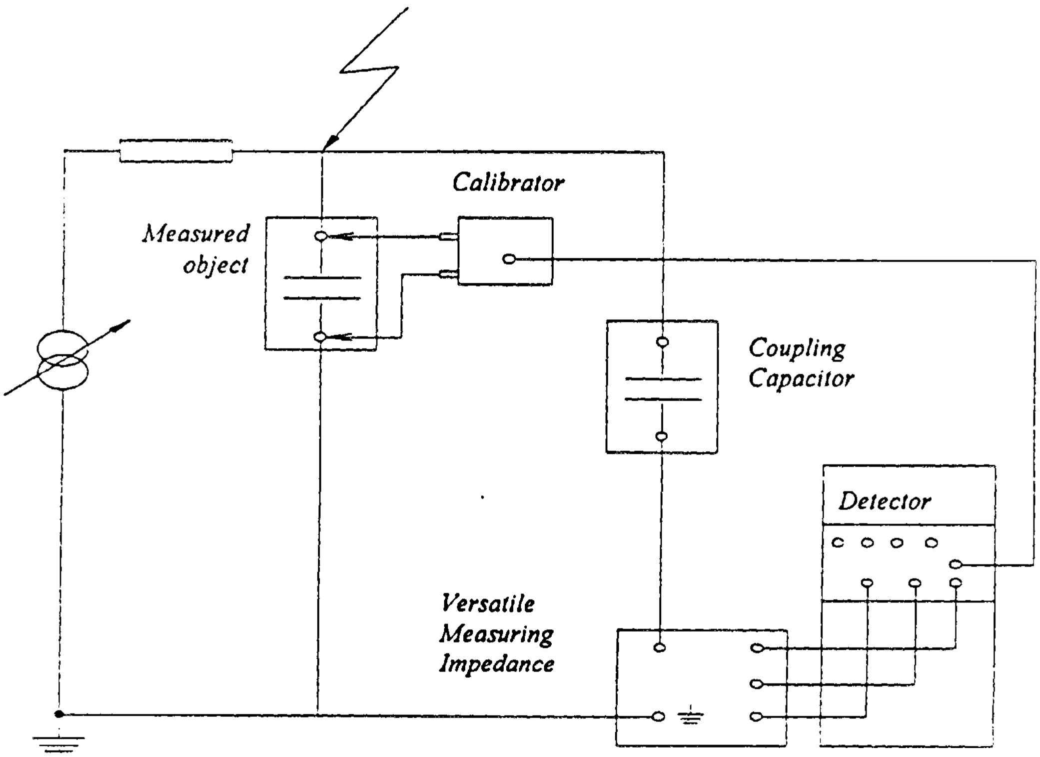

Fig. 3: Partial Discharge Measurements Principal Diagram

The results of all the mentioned prophylactic measurements are logged. Thus, an accurate idea of the nuclear power plant electric equipment present-day insulation condition is available. Ten years experience in generators and transformers measurements provides a serious basis for possible measured anomalies review. Each machine has its own „curriculum vitae". It makes it possible to observe annually either a slightly deteriorating insulation condition or a step change in it; this indicates a possible failure of the machine. Copies of measurement logs are handed over to both the equipment owner and Maintenance Division engineers. If the group specialists give recommendations to repair a machine, the maintenance staff will do it. Following each repair work, the machine is subjected to repeated complex measurements prior to putting back into service.

In 1992 the TETTEX INSTRUMENTS Co. mounted the capacity, loss factor, ohmic resistance and partial discharge measuring devices into an AVIA FURGON truck, subjected the devices to certification tests, and connected them to a processing and evaluation computer. Thus, a mobile measurement center was completed that enables to make the mentioned HV measurements reliably and promptly both on and off the NPP site.

2. THERMOVISION MEASUREMENTS OF CURRENT CONNECTIONS

Thermal defects, especially in cable corridors, both indoor switching stations and outdoor switchyards and in electric machines themselves, represent dangerous factors. Above all, the fire risk may occur, as well as major electric equipment may fail to operate which results in the NPP nuclear safety violation. Current connections in electric equipment represent a basic source of thermal defects. The connections are made by means of different technologies: pressed connection, screwed connection, contacts of switches, circuit breakers, contactors, etc. The current connections are inspected by means of a thermovision system which operates within the infrared section of the electromagnetic spectrum. Thermovision measurements are made in 110, 220, and 400 kV switchyards, unit transformers, generator outlets, generator switches, generator collecting equipment, 6 kV, 0.4 kV switching stations and 6 kV, 0.4 kV power cable current joints. The above-mentioned equipment are inspected once a year, prior to the reactor unit major overhaul. VHV equipment are inspected twice a year. In addition to the regular measurements, generator stator windings are measured during an inductive warm up and measurements are made on some non- electric technological equipment.

The electric equipment inspection periods are specified by directions. Detected failures are removed by the maintenance staff during reactor unit major overhauls, more severe failures are removed as soon as possible. The value of temperature difference between the current connection and its incoming feeder is the criterion of a thermal defect occurrence. If both the current connection and its incoming feeder are of equal temperature under the conditions of both a steady thermal state and a constant current flow, there is no thermal defect in the connection. If the current connection is warmed up in relation to the incoming feeder, i.e. the temperature difference is not equal to 0° C, the current connection is considered to be defective. In practice, the defect is in most cases identified reliably due to thermal gradient detected along the current route in the neighbourhood of the connection, even if the defect is small. The group specialists are able to detect a warm up by means of the thermovision set. The accuracy of detection is ± 0.1° C for materials with a defined emittivity the value of which does not drop too deep below „1" (this condition is met in practice). The extent of a defect is defined by the warm up value (°C). This value is approximately kept even if the ambient temperature fluctuates. That is why if a defect is observed in function of time, we can judge by the warm up value whether the defect remains unchanged or expands, while the ambient temperature can even drop.

The special prophylactic measurement group has a couple of thermovision measurement workplaces available. One of them is specialised in the NPP V 1 electric equipment inspections. It is equipped with the AGEMA 782 SW thermovision set that comprises: a thermovision camera, a monitor, accumulator batteries, a videorecorder and photocameras for both thermal and real photographs. This set is of older design. Isothermic degrees must be calculated into degrees of Celsius by means of a programmable calculator. The other workplace is specialised in the NPP V 2 electric equipment inspections. It is equipped with the AGEMA 880 LWB thermovision set that comprises similar components to the AGEMA 782 set. Its sensitivity is, however higher and isothermic degrees are calculated into degrees of Celsius by means of the HUSKY computer. The computer is connected to a monitor. It runs in the real-time mode. Moreover, the camera can be controlled remotely. This is especially appreciable when measurements are made near strong current fields, e.g. in case of the generator inductive warm up.

Both the workplaces are operated in the following way:
equipment that have already been enumerated are inspected by means of the mobile thermovision set in compliance with their significance. The group specialists have recorded and registered data on all the power plant switchboards, as well as all 6 kV and 0.4 kV power cable joints. The latter, situated in cable corridors, have been labelled to facilitate their later use.

If a defect is detected, it is recorded by the videorecorder with the accompanying audio explanations, involving both a more detailed defect description and the date of the defect detection. Both thermal and real photographs are taken, because a thermal picture differs much from a real one which makes the orientation more difficult. The measurement results are further processed. More complex thermal pictures are processed by means of the TIC 8 000 computer code providing a very large scale of measured picture processing including historical defect data collection.

The group specialists hand the log of reactor unit equipment thermovision measurements over to both the maintenance staff and the equipment owner two weeks prior to commencing the reactor unit major overhaul. The log involves both a list of measured equipment and a list of defects; each defect item includes either a thermal picture photograph or a colour picture generated by TIC 8 000, e real defect photograph, date of the defect detection, a measured value of the defective current connection temperature difference, temperatures of surrounding properly operating connections, and, finally, a value of current flowing through the connection.

There are two basic measurement techniques: direct temperature measurements and temperature measurements by means of a reference source.

The reference source technique has proved to be better for the group specialists. If an accurate reference temperature source is available, both temperature and warm up can be measured with a high accuracy of ± 0.1° C. Either the switchboard structure or the related equipment are used as the reference temperature source. The object temperature value is not measured with a high accuracy (the ambient temperature referred to as a reference source can fluctuate by ± 1° C), but the value of warm up that is decisive for the measurement purposes does not lose its accuracy, especially at lower temperatures.

The advantage of this measurement technique consists in a good accuracy with which the warm up can be determined and smaller amount of efforts needed to make measurements, because lower number of measurements are to be made to determine the value of warm up. This results in both shorter defect recording time by the videorecorder, as well as less time needed to process the defect records (an advantage with respect to a large number of recorded defects).

If a more severe defect occurs, e.g. a high warm up of a disconnecting switch in a 0,4 kV panel, this results in a remarkable warm up of the switchboard construction that is considered to be a reference source with a constant temperature. In such a case, if possible, the direct technique of both the construction and the faulty object temperature measurement is used. The measurement accuracy still complies with the measurement purpose.

The thermovision measurements have been made since 1986. A sufficiently wide overview of the electric equipment current connection condition has been got at the NPP during this time period. While 120 to 130 thermal defects were detected at one reactor unit annually during the first years, this number dropped to one half nowadays. In 1992 110 kV switchyards thermovision measurements were made to order of Vodné elektrárne Trenčin Company. More than 10 defects were detected in each of inspected switchyards that are identical to the NPP Bohunice VHV switchyards, the warm up values being relatively high - up to 25° C. 1 thermal defect per a switchyard is detected during the inspection in the NPP Bohunice at the most at present. This proves doubtlessly the significant contribution of the thermovision measurements to the nuclear safety.

SYSTEMS FOR NOISE DIAGNOSTICS OF WWER NUCLEAR POWER PLANTS

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ABSTRACT

The aim of this paper is to give a short overview of the noise diagnostics system developed by Hungarian firms which are in operation in WWER type NPP Units. Giving a list of systems developed for noise diagnostics of WWER reactors we present their main characteristics, their goal and some of their achievements. The second part deals with the problem of acceptance of noise system by NPP and regulations.

INTRODUCTION

In spite the fact that fluctuation measurements in nuclear reactors has been started as early as the nuclear age, since Feynman and Rossi had applied the noise methodology named after them to measure important parameters of nuclear process from the very beginning, noise diagnostics is still not a part of standard procedures for Nuclear Power Plants. We believe that the delay was caused mainly by technical difficulties to get reliable statistical parameters with early electronics. After the development of the past twenty years in electronics and computation technique the fluctuation measurement became a very effective tool to detect, monitor the malfunction of an industrial system or to estimate some of its parameter. Today this method is one of the most rapidly developing tools and more and more widely used for monitoring purposes, for early failure detection, for enhance the reliability of the given system helping to maintenance work, and to improve the safety via reliability of a Nuclear Power Plant [1]. The time has come that noise diagnostics can became standardised procedure for nuclear power plants.

PERMANENT SYSTEMS DEVELOPED FOR NOISE DIAGNOSTICS OF WWER PLANTS

Here we restrict ourselves to those permanent noise diagnostics systems which were developed by Hungarian firms for WWER type NPP. It is well known, that Siemens also has installed several systems on WWER plants and there are some system developments in Slovakia [2], in Czech Republic [3] (we are trying to refer to publications which might be easier to access and differs from [1] where appropriate). Also Russian firms has started to develop different diagnostics systems. Perhaps the best know is the VDS produced by TURBOTEST for turbine diagnostics [4], but Khurchatow institute has also installed an experimental system for WWER type reactors in Kalinin NPP [5].

PDR This used to be the abbreviation for Paks Reactor Diagnostics measuring chains when the first Unit was started in 1981. They contain amplifiers for noise measurement using incore self powered neutron detectors, top-of-core thermocouples, some special pressure fluctuation transducers and a specially designed set of amplifiers for excore neutron detectors, which enabled us to attach noise system to safety related channels and to make noise measurements on pulse mode signals. The first solution has proven its ability, channels still work after 15 years. Their modification were used in later systems. Today electronics allow to attach noise system directly to plant amplifiers (see ZOMBI), but the solution for excore detectors still unique for WWER reactors if one wishes to use the safety channels.

ARGUS is a vibration monitoring system using accelerometers to monitor vibration behaviour of the components of the primary and secondary loops of WWER type reactors[6]. In its first version there were simple measuring channels and a CAMAC based system, later PC based sampling, data evaluating and processing system was also included which contained also a really expert shell based expert system for turbine diagnostics.

ALMOS is an Acoustic Leakage MOnitoring System, based on high frequency acoustic transducers. Its data evaluation system based primary on rms level [7]. Later analysis package was included to the system relying on rise time and frequency content and arrival time of the signals.

DIS (Diagnostical Information System) can be broadly defined as an interactive computer-based information system, which is used to facilitate the implementation of a plant-wide failure monitoring and diagnostical system in large-scale systems [8]. It was born to apply more and more sophisticated mathematics in reactor noise analysis and interpretation. DIS includes BDIR94 data acquisition system as well as RTiME NEtData, which is a diagnostical resource owning with full variety of contemporary tools for diagnostics. One of the most important feature of RTiME is the non-parametric modelling of the measured signals using Autoregression, Moving Average and other more sophisticated models with built in probability analysis. It can automatically discard the unreliably measurement giving the chance to the user to deal only with reliable measurements. It works as a supervisor system for reactor noise and vibration measurement at Unit 1 and 2 at Paks NPP.

CARD is a Computer Aided Reactor Diagnostics system, which is capable to collect, to process fluctuating parts of signals from the reactor [9]. Its inputs accept signals from in-core self powered neutron detectors, excore ionisation chambers, thermocouples, pressure fluctuation transducers and some of the accelerometers mounted on reactor vessel and in primary loops. System automatically estimates FFT spectra and MAR models, trends of parameters. All those are compared with previous values. A physical model based expert part helps to user to find occurrences like: core barrel motion, incore vibration, stability of the feedback system, hot spots in the reactor. Signal validation and parameter estimation (for example reactivity coefficient estimation, thermocouple time constant estimation) complete the system.

HELPS is a Hungarian Expert Loose Part System [10]. It is completely model based. Firsts a non-parametric modelling (using a combination of autoregressive modelling with sequential probability ratio test) helps to find if there is any abnormal occurrences in the system (in primary loops of NPP). All deviation from normal statistical behaviour can be found even in that case when rms value does not changes at all. Then the found occurrences are analysed using adaptive learning algorithm, which uses part rms, and also an expert shall comparison of all moments and signatures from the operator room. Finally this kind of analysis lead to more reliable loose part detection with less false alarm rate.

ZOMBI is a system under installation which enables the CARD system to reach all in-vessel signals in WWER reactor [11]. There are many in-vessel signals: 216 thermocouples and 288to336 incore neutron signals in WWER type of reactors. The whole core diagnostics can be solved monitoring periodically those using the advanced diagnostics methods.

JEDI is a system under development, which partly based on CARD system. It also includes new methods (like Kalman filtering techniques) and covers methodology for leak detection and sensor validation as well [11]. It should be recognised that with growing amount of information the man machine interface part of such half automated diagnostics systems becomes very important.

In those systems which have actuators automatically driven by the system the importance of the man machine interface maybe less important. None of the diagnostics system has really actuators. Diagnostics it means to recognise the malfunction, to give some information on that. It may give even hints, but usually decisions taken by experts. Diagnosis it means always an early warning and early failure detection. The parameters of the given system are still within the allowed limits (both from regulatory point of view and from physical point of view). If they are out of range then the system must be halted. When we speak about diagnostics the system is still running, but some tendencies in it are going into the direction which can lead out from the allowed range. That also means there are still time to take decision. there is no need to attach any automatic actuators to the system.

Diagnostic system are not safety systems but systems to improve reliability of NPP hence they assist to the safety. They are information systems which are safety related. How to arrange the information? How to present it? How to drive the attention to the important occurrences? How to ensure that the important part would not be hidden by numerous miscellaneous effects? This is very important for such system.

A good man-machine interface can help very much in that. This is the final goal of the development of the system of JEDI.

SOME IMPORTANT RESULTS ACHIEVED BY THOSE SYSTEMS

We do not promise here to give an exhausting list of event of all occurrences detected and analysed by those systems listed above. Partly because they have been published earlier (see references). We cannot avoid to mention some of them to convince the reader: these systems have passed the period of basic development, they became commercial, they became regular systems, they are reliable, one can trust them. If they show something there is something to be investigated and solved in the given Unit. If they do not show any deviance, the Unit works in normal condition. But the most valuable result from these system still serves for maintenance work. They reduces the maintenance cost preparing the maintenance period.

Core barrel motion is a real concern for WWER type pressurised water reactors. They have four or six primary loops and their unbalance can be a cause for pendular movement. But usually the size of such motion does not reaches dangerous value. The failure of the core hold down springs can be a cause of a really dangerous pendular motion of the core barrel having different constant of elasticity for different springs. There are six such non-linear springs around the top of the core in the vessel. Very well documented such dangerous core barrel motion has been reported from Nord NPP [12]. It is well know there was similar problem in Khmelnitsky NPP and there are rumours from other Russian WWER having such problems. Therefore we believe that having a core barrel motion monitoring program in our CARD system it gives a very important tool for the operators. The proven sensitivity of the method in the given realisation is 10 microns (or better). Until now the maximum of the core barrel motion recorded in Paks NPP was 22 microns. It has been proved in Kalinin NPP when a measurement was carried out in an unbalanced situation that the program really shows the unbalance [9]. Consequently in spite the fact that there was no dangerous core barrel motion recorded during the total

13 reactor years by CARD systems, operators were convinced that there was no such danger in given Units.

Leakage is another great concern of WWER reactors. They suffer in frequent leakages. Such leakages were reported almost from each NPP having WWER. Perhaps the most successful system to detect leaks in primary loops of WWER is the ALMOS system. An advantage of that system is that it gives reliable result at the upper block of reactor vessel, where control rod driving mechanism and top sealing of the reactor vessel takes place where leakages are frequent. But it gave also good results on horizontally placed steam generators even during installation of ALMOS at Kalinin NPP in an automated mode. We could also notice the insufficient repair of that leakage, though it was not very easy to convince the maintenance personal about this fact [7]. Leakages at Paks NPP were found: at the valve of volume compensator (pressuriser) in 1991, and a 0.2 kg/h leak was monitored during the whole fuel campaign in 1993.

Perhaps the third most frequent malfunction in WWER reactor detectable by reactor noise diagnostics is the incore vibrations. Such vibration has been observed especially in WWER-440 type which have seven control assemblies consisting of a fuel assembly and a follower on the top of each. The smallest vibration of the follower which is always inserted into the core to certain level will results in detectable peaks in the spectra of nearby incore neutron detectors. In the case of an excessively vibrating controller [13] even far field neutron detectors can see such vibration, and this can be used for incore vibration monitoring [cf. 14,15].

Vibration diagnostics of the main component of primary and secondary loops became today well standardised field of noise diagnostics. One can find in international standards (ISO) limits for malfunction of rotationally machinery or other type of equipment. The knowledge based diagnostics for turbine of ARGUS system opens the possibility not only detecting excess vibration but also it giving hints, what is the cause of the vibration.

Another group of the occurrences in which monitoring of fluctuation can help is the malfunction of the sensors or simple the sensor degradation. This is also a very important field of noise diagnostics since it can predict the malfunction of the sensors and in this way it can help tremendously to maintenance work. Especially valuable are the results of such system when preparing the maintenance during the refuelling period. There are more then 500 in-vessel thermocouples and neutron detectors in WWER reactors, which can be exchange only during refuelling period. In the same time regulation does not allow to work with the Unit if more then 10% of those sensors has a failure. CARD, ZOMBI, JEDI, ALMOS, ARGUS all use algorithm to find defective sensors or measuring channels. Since CARD and JEDI works with standard instrumentation of NPP they are extremely useful for maintenance work.

Finally, parameter estimation is a developing field of noise measurements. A good example for that is the estimation of reactivity coefficient which is one of the most important safety parameters of all reactors. Noise measurements enable to follow the changes of this parameter without interfering to normal work of NPP and on-line [16]. Incore coolant velocities and hot spot can be estimated using transport effects measured by CARD as well. Another example for parameter estimation is the decay constant estimation which characterises the feedback loops in the given system, thus it gives hints on stability of the system. In fact this has more practical importance for boiling water reactors and a special stability measuring devices has been developed by Swedish researchers [17]. A good example was reported from Germany how to use this methodology in PWR reactors [18]. CARD system has also decay ratio monitoring capability and it has proved its ability to notice abnormal behaviour due to closed main valves, which are characterising again only in WWER reactors [9].

THE RELATION OF NOISE SYSTEMS TO REGULATIONS

In the previous section we listed some successful applications of noise diagnostics in different NPPs. In spite the fact that there has been numerous successful detection by those permanent system still nuclear power stations tend to neglect these results.

Here follows a story of an early case of a core barrel motion detected in Rheinsberg NPP. During an international measurement exercise which was aimed to detect reduced flow rate in an experimental fuel assembly, excore neutron detector signals were also recorded. They were elaborated routinely with the standard methodology which included also core barrel monitoring. A typical core barrel motion characteristics was found and connected to the spectra of a main coolant pump as the origin of the motion. It was published in an IAEA seminar [19]. It is typical that the power plant management was not happy at all with that situation. It turned out that German colleagues has noticed earlier that movement. They also made much more recordings on pump vibration and the pump malfunction has been repaired even earlier then the inadversively published paper of the author appeared. But they were not allowed to publish these results [20]. One could say this happened in former GDR before the changes. But author has similar experience in more developed countries and at home as well. The management of the NPP is never interested in publication of such results. Even if they accept that the warning was coming from noise diagnostics they consider that as their know how. It is even more typical that the know how does not contains information on the fact that warning was coming from noise diagnostics.

Typically noise diagnostics gives only hints that there are some malfunction in the system and it is coming from some place. Using this hints it is advisable to go there and to test the given equipment with standardised procedure. If it also shows malfunction then according to regulation it has to be recorded. (If it does not then typically the case is dropped, no records preserved). Regulation describes usually also how to make records, what indications of the standardised procedure should be recorded. Usually it does not contain that initiating information had been coming from noise diagnostics. Typically, record contains an information that parameters prescribed by standardised procedure has been measured at the given date and they exceeded (or not) the allowable limits. Sometime even the management of the NPP does not know that the indication was coming from noise diagnostics. Maintenance people owning with standardised procedure are interested to hide the fact that hint was coming from diagnostics. It might seem that they did not applied the standardised procedure in due time that is their failure.

We wasted quite a space to demonstrate what was (is) happening in nuclear power plant with information coming from diagnostics. This is typical everywhere. The only way out of this situation could be if the nuclear regulations consider the diagnostics as compulsory or at least strongly advisable. It could help a lot if such recommendation would be elaborated and recommended by IAEA. It is an experience also that recommendations of IAEA found their way to the national nuclear regulations.

Happily in the past few tears an intensive growth on the number of standards can be observed in this field and it was also announced that an European standard is under development. At the end of the reference list we gave some of them [21, 22,23,24].

To make a recommendation we need to collect those occurrences in nuclear power plants which has been detected, localised and explained using noise diagnostics. We have to show the reliability, usefulness and applicability of those methods. We have to find the warning and alarm limits for such occurrences as: core barrel motion, incore vibration, hot spot detection, etc. Finally an international team should elaborate recommendation on noise diagnostics fro different type of nuclear reactors.

CONCLUSIONS

A full set of noise diagnostics system has been developed during the past 15 year for WWER reactors. They have been proved their ability for early detection the malfunction of the system, to give early warning of sensor degradation, to estimate some parameters which have importance fro safety of the reactor, without interfering the work of the given Unit.

In the same time regulations neglect these results. Except of loose part monitoring, which is strongly advised in US an in some European countries , application of noise diagnostics is not mentioned in official material, regulation of NPPs. For WWER reactors there exists a written directive (Ukazanie) from the general constructor since 1988 in which he suggest to use the diagnostics in WWER rectors, but it has never been really included into existing regulation of countries having such reactors.

We believe that results of noise diagnostics are convincing. Permanent system and analysis of some cases has proved the power of such methodology. It is time to collect all knowledge in this field in the frame of an international co-operation and to elaborate them concluding in suggestion for introducing noise diagnostics as compulsory tool in regulations in countries having nuclear power plants.

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TG 220 MW HYDRAULIC CONTROL SYSTEM DIAGNOSTICS

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ABSTRACT

In 1990 both settings and diagnostic actions of individual control elements in the oil control systems of ŠKODA K-220 MW type turbines began to be taken by means of measurement equipment. The original idea consisted in setting conditions for a uniform oil control elements testing system implementation at the NPPs V-1 and V-2. Appropriate modifications were performed for that reason - control oil sensing lines were installed making it possible to connect the measurement equipment to them safely even with the turbine running.

The measurements themselves are made by appropriate measurement equipment (Servogor line recorders, Dynisco pressure sensors, Phillips pressure sensors, ASL position sensors, Phillips position sensors). The whole system was completed during its implementation (fixtures, power supplies). There are possibilities of complementing the system by HARDWARE equipment and SOFTWARE.

In 1990 measurements were made on all 8 turbines (TGs) upon completion of their repairs at the NPPs V-1, and V-2, the results being better or worse. The measurement results were only of information significance, their purpose was to provide an overview of states of individual control systems, to adjust measurement procedures, incorporate the activities in the repairs schedule and persuade competent SE-EBO specialists of the system advantages.

Since 1992 the hydraulic control system diagnostics is performed before repairs are started at the corresponding reactor unit. This procedure enables both early failure detection and repairs performance during scheduled small-scale repairs (BO), extended major overhauls (RGO) and type major overhauls (TGO) of turbines.

The TG power output control system comprises a hydraulic and an electronic part. TG speed, power output or the main steam header pressure (HPK) depend on the steam flow at the turbine inlet. The steam admission into the turbine is controlled by four control valves and one by-pass valve in case of the HP part and by four capture flap valves in case of the LP part.

The control valves opening is determined by the secondary oil pressure (p_2), whereas the capture flap valves opening is determined by the tertiary oil pressure (p_3). The hydraulic part comprises convention speed control elements (hydraulic controllers, primary transformer, secondary transformer) and protection system actuators (load limit adjuster, electric accelerator, major relay, safety device relay, quick-operating relay).

The turbine protection system is mainly of a hydraulic design. It, however, also comprises electrical and I & C devices which trigger turbine trip pulses via electrical lines to protection system elements in cases of controlled variable deterioration. The task of the ŠKODA K-220 MW turbine protection and control systems is to provide both the turbine speed and power output control to the setpoint value. Diagnostic measurements were aimed at getting an overview of both technical and functional states of all power output control elements. Principally, it can be stated that some deficiencies of a design nature originating from the manufacturer's factory were revealed and some other deficiencies related to hydraulic control elements functionality were identified more closely by the new method.

I. List of TG 220 MW Hydraulic Control System Tests

1. Tests Performed on Taking the Turbine out of Service for Repairs

Before the reactor unit is shut down for repairs, it is necessary to agree upon the scope, time schedule and co-ordination of the tests with the unit operation staff.

The measurements themselves are initiated by connecting pressure sensors during the turbine rated output operation closely before it is taken out of service for repairs. The whole measurement process is concentrated on measuring the secondary oil pressure (p_2), tertiary oil pressure (p_3), primary oil pressure (p_1), active power (N_{SKUT}) and speed functions against time at this stage.

The tests do not interfere with the reactor unit shut down process. It is only that after the turbine has been disconnected from the grid, it continues to run at n = 3000 rev/min for approximately 10 to 15 minutes. Tests of the electric accelerator and the protection system division by means of the test relay actuation are made within this period of time. The nature of those measurements consists in verification of the accelerator action and p_1, p_2, p_3 pressures and turbine speed responses in time, as well as measuring the time sequence action to the electric accelerator magnet. This measurement is aimed at verification of the control elements reaction to closing the steam admission in the turbine within a short period of time - approximately 2 seconds. During the test of the protection system division that is made by the tester magnet actuation, functions of all those elements involved in the process of the protection system division into two halves are verified. The test result involves an overview of both responses and reactions of speed safety relay (RPZ) and major relay during the division process including primary (p_1) and control (p_{OVL}) oil pressure trends measurements.

This test is one of the most important tests from the point of view of the reactor unit safe operation significance, because it makes it possible to test the protection system proper functioning in case of an electric pulse triggered to the quick-operating relay (rýchlozáver) during the reactor unit rated power output operation.

1.1. Turbine Trip by Means of an Action to the Quick-Operating Relay

When the basic diagnostic measurements are accomplished, the turbine is tripped by means of an action to the electric quick-operating relay. During the process involving closures of all stop valves and flap valves the following measurements are made:

- ⇒ TG run-out curve,
- ⇒ characteristics of hydraulic controllers,
- ⇒ main oil pump (HOČ) characteristic.

2. Tests Performed after Taking the Turbine out of Service for Repairs

The complete set of tests is performed after the reactor has been shut down or the turbine has been taken out of service for repairs - during the cooling stage when the turbine is driven by the rotating machine (NZ). After all appropriate technological nodes have been isolated and a temporary primary oil source has been installed, the complete control loop is inspected. At this stage of individual oil control elements tests all convention control elements are measured including servo-units of control valves (RV) and capture flap valves (ZK). 8 hours of undisturbed work are necessary to be allowed for the tests performance including the possibilities of bringing all the turbine control and operation elements in the initial operation state (zasmeknutie turbiny) and opening control valves within the range from 0 to 100%.

2.1. Static Characteristic of Conventional Speed Control Elements

This area involves a group of control elements providing fluent changes in TG speed and power output. The trend of the characteristic, the insensitivity to changes in oil pressure is verified by the measurements themselves including the failures specification.

2.1.1. Primary Transformer Static Characteristic

The primary transformer generates the secondary oil pressure that is inproportional to the primary oil pressure and proportional to force of the spring prestressed by the power converter or medium speed converter.

Following is a list of primary transformer tests:

- ⇒ identification of the relationship between the secondary (p2) and primary (p1) oil pressures with regard to the preset unevenness,
- ⇒ primary transformer insensitivity evaluation.

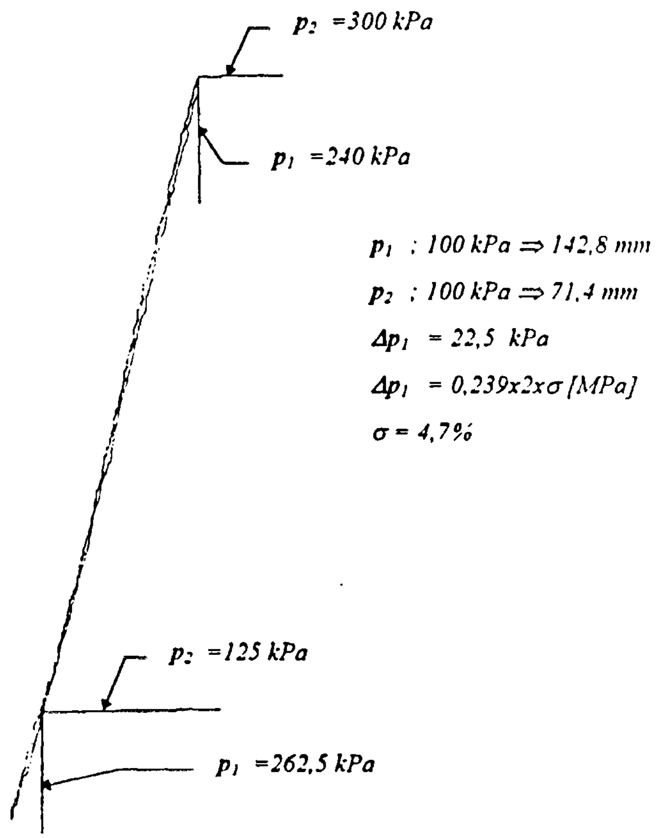

Fig. 1.: Primary Transformer Static Characteristic

2.1.2. Secondary Transformer Static Characteristic

The secondary transformer is incorporated in the secondary oil circuit. Both static and dynamic couplings among control valves (VTRV) and capture flap valves (NTZK) are generated by the secondary transformer. A change in the secondary oil pressure (p_2) results - by means of the secondary transformer - in a change in the tertiary oil pressure (p_3).

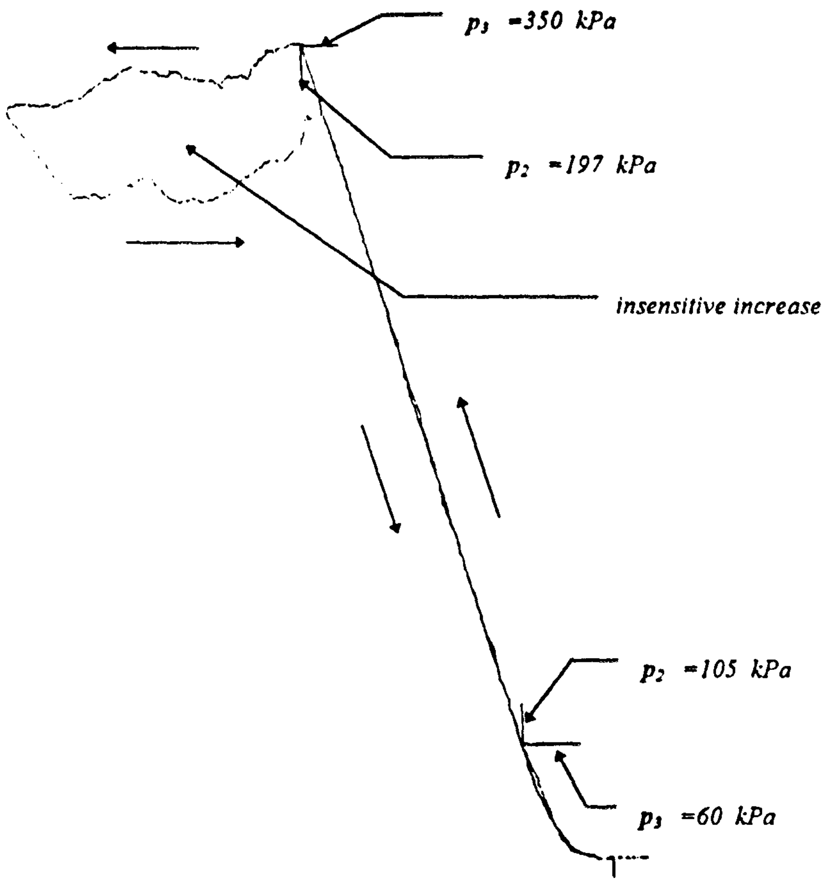

Fig. 2.: Secondary Transformer Static Characteristic

Following is a list of secondary transformer tests:

⇒ identification of the relationship between the tertiary (p_3) and secondary (p_2) oil pressures with regard to couplings converter positions „Left" and „Right",

⇒ secondary transformer insensitivity evaluation.

2.1.3. Control Valve Static Characteristic

The control valve (VTRV) servomotor starts opening the valve when the secondary oil overpressure (p_2) has achieved 115 kPa. The course of the subsequent control valve opening by the servomotor resulting from pressure p_2 is defined by the servo-unit characteristic.

Following is a list of control valve tests:

⇒ identification of the relationship between the valve lift and pressure p_2,

⇒ evaluation of the deviation from the drawing-based characteristic,

⇒ insensitivity evaluation including the failures specification,

⇒ determination of the valve closing time in case of p_2 pressure loss - an action to the test electric accelerator magnet,

⇒ determination of the valve closing time in case of an action to the test relay magnet,

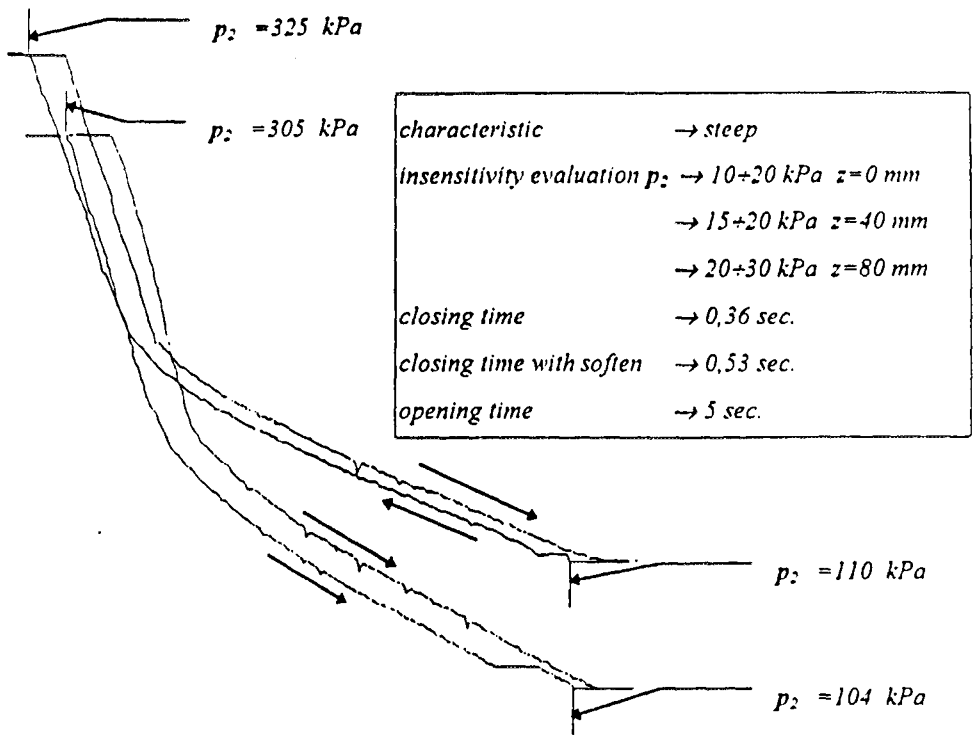

Fig. 3.: Control Valve Static Characteristic

3. Tests Performed on the Oil Control System Setting after Repairs

During reactor unit technological equipment repairs and following evaluation and failures specification, repairs and revisions are made on those turbine oil control system elements which showed deviations or functional deteriorations during diagnostic measurements. The evaluation process itself requires not only long-term professional experience and a high technical level, but also a perfect knowledge of the repaired equipment.

Verification of the action correctness is only made after all TG oil system activities have been completed. Before the oil control system settings are made, the complete system is rinsed. The oil charge temperature must be at least 50°C. All the TG control and protection system elements are set up and individually adjusted in compliance with their drawing-based characteristics at the first stage of the tests implementation. Following the adjustments, measurement equipment is prepared and the oil control system diagnostics itself is started.

3.1. TG Control System Static Characteristic

3.1.1. Primary Transformer Static Characteristic

⇒ identification of the relationship between p_2 and p_1 pressures with regard to the preset unevenness.

⇒ primary transformer insensitivity evaluation.

3.1.2. EHP-08 Power Converter Static Characteristic

⇒ identification of the relationship between p_2 the percentage of EHP-08 rotation at p_1 = const.

⇒ EHP-08 scope identification,

⇒ power converter insensitivity evaluation.

3.1.3. Secondary Transformer Static Characteristic

⇒ identification of the relationship between p_3 and p_2 pressures with regard to coupling converter positions „Left" and „Right",

⇒ secondary transformer insensitivity evaluation.

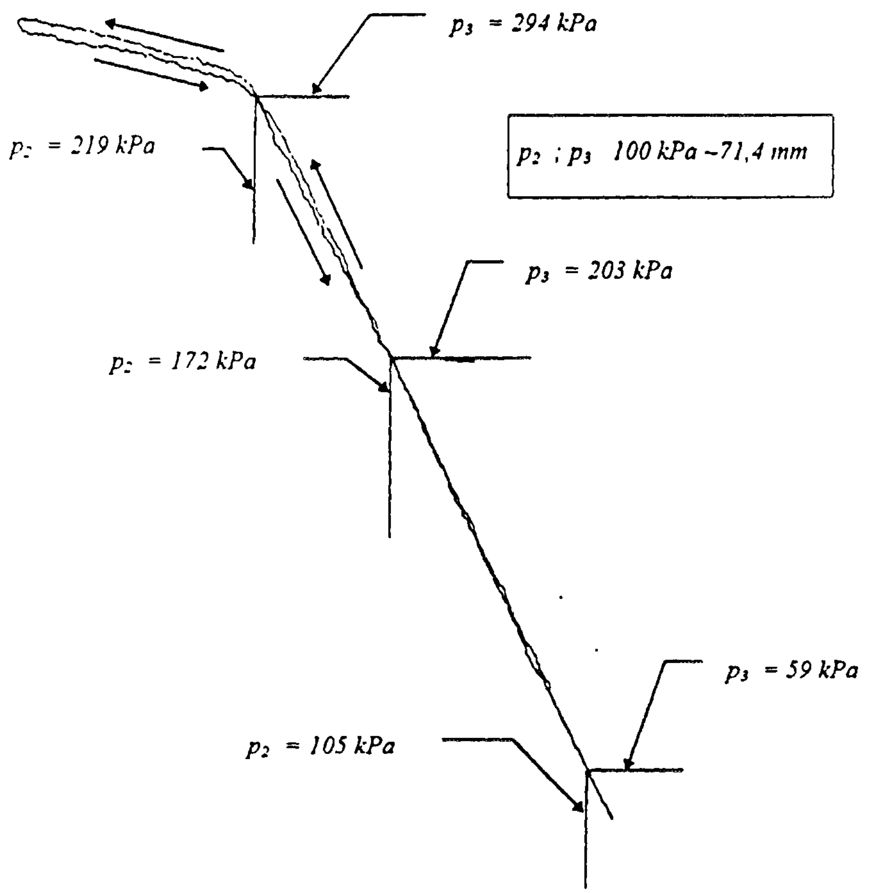

Fig. 4.: Secondary Transformer Static Characteristic after Repairs

3.1.4. Control Valve (RV) and Capture Flap Valve (ZK) Static Characteristics

⇒ identification of the relationship between the valves and flap valves lifts and the secondary p_2 or tertiary p_3 oil pressure,

⇒ evaluation of the deviation from the drawing-based characteristic,

⇒ insensitivity evaluation,

⇒ closing time determination for each RV and ZK in case of p_2 or p_3 pressure loss,

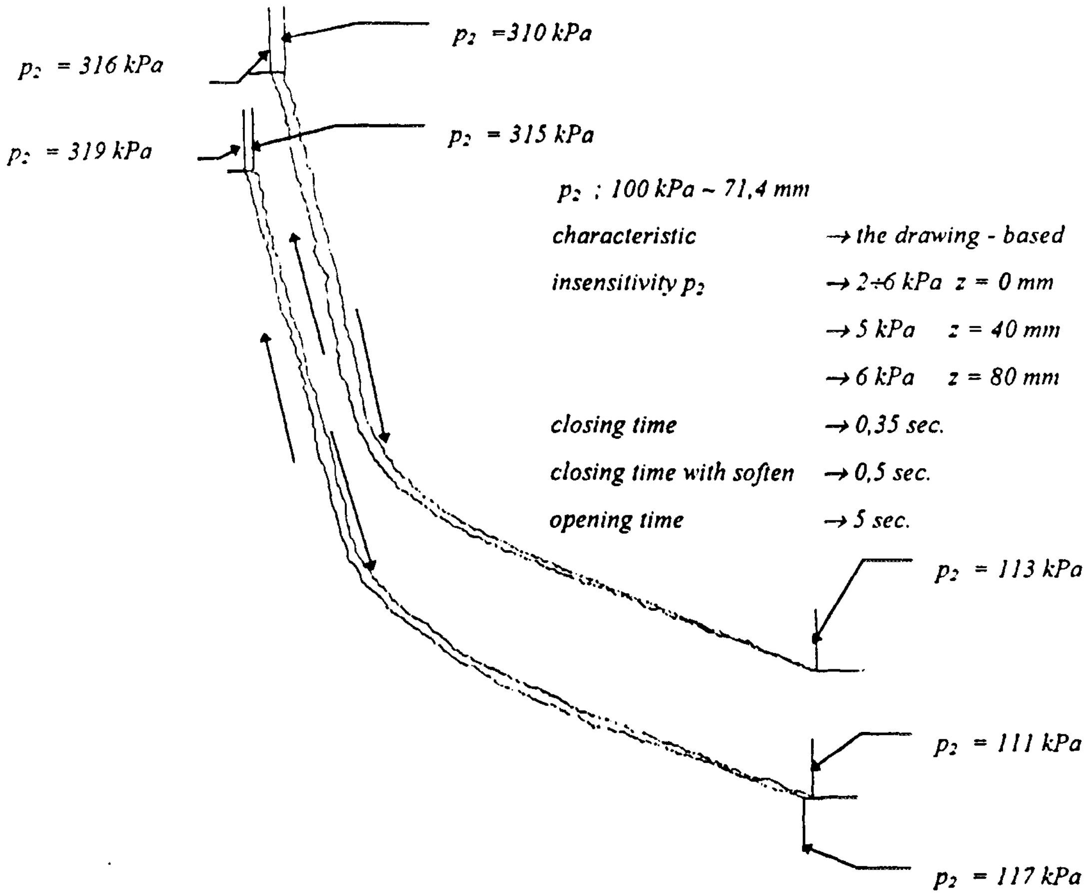

Fig. 5.: Control Valve Static Characteristic after Repairs

3.1.5. Load Limit Adjuster Static Characteristic

⇒ identification of the relationship among p_{OVL}, p_2 pressures and the load limit adjuster lift.

⇒ evaluation of bringing the load limit adjuster in the initial operation state and its disconnection.

⇒ p_2 scope identification.

3.2. TG Protection System Diagnostics

3.2.1. Action to the Electric Accelerator Magnet

⇒ identification of p_3 and p_2 pressure loss times in case of full energizing the electric accelerator magnet,

⇒ identification of full p_3 and p_2 pressure recovery times after releasing the magnet,

⇒ electric accelerator proper functioning evaluation.

3.2.2. TG Trip Resulting from an Action to the Electric Quick-Acting Relay Magnet

⇒ identification of $p_{OVL\text{-}PR}$, $p_{OVL\text{-}ZAD}$, p_{RZ} pressure loss times in case of pushing the quick-acting relay magnet in.

3.2.3. Simulation of a TG Trip Resulting from Increasing Speed

⇒ identification of tripping (vysmekovaci) pressure p_1 for both halves of the safety device relay (RPZ).

⇒ identification of loss times of oil pressure p_{OVL}, p_{RZ} in case of tripping the front and rear halves of the safety device relay (RPZ).

3.2.4. Quick-Acting Relay Circuit Test by means of an Action to the Tester Magnet

⇒ evaluations of safety device relay, major relay and test relay proper functioning.

⇒ evaluation of p_{RZ}, p_{OVL}, p1 pressure trends during the test,

⇒ test time relationships identification.

4. Tests Performed on the Turbine Start-Up after Repair

Repair actions are completed at the appropriate NPP reactor unit technological nodes at this stage and the turbine is prepared to the control and stop valves set warm up. During increasing the turbine speed the primary oil pressure p_1 and speed measurements against time are made. After the turbine speed of n = 3000 rev/min has been achieved, the primary oil pressure p_1 is adjusted (the control oil temperature must be in correspondence with the temperature held during the turbine rated power output operation).

A set of tests performed during the turbine at idle run are to bring an overview of both dynamic and functional qualities of control system elements after repairs. The protection system as a whole and the oil control system functionality are tested in the final part.

Following finishing the diagnostic measurements, the turbine is taken over to perform subsequent tests included in the preparation process for phasing to the national grid.

IV. Assessment of Practical Measurement Results

Based on results that have been recorded since 1992, it can be stated that some deficiencies of both design and technological natures were revealed by the diagnostic measurement system. Modifications related to the control oil sensing lines installation were implemented in parallel with the general revision of all TG speed and power output control system elements, as well as TG protection system actuators.

This procedure was aimed at the individual component technical states inspection (bellows, valve seats and cones) and at the separate settings of prescribed assembly values in compliance with the manufacturer's technological procedures. This was a starting point. After it was implemented, the turbines oil control systems diagnostics itself was initiated.

Occurrences of eddy currents were revealed by the diagnostic system (in case of insufficient connection between the TG rotor system and the frame). The eddy currents deteriorated surfaces of function areas by means of their electroerrosive effects. This phenomenon becomes evident by depositing some material on contact areas of pistons, cones, seats, casings. All this results in deterioration of reactions to changes in oil pressures, i.e. large time delays leading to possibilities of TG trips caused by drops in oil pressures. Increased hysteresis was measured which was another benefit of the diagnostic measurements. It was a signal of some mechanical state deteriorations in the appropriate technological node. The diagnostic measurement benefits also included the detection of delayed reactions to changes in oil pressures. A thorough inspection showed leakage in the oil system or certain NTZK bearings mechanical state deterioration.

The complete scope of the above mentioned knowledge makes its large-scale contribution to the faultless running of turbines installed at the NPPs V-1 and V-2.

DIAGNOSTIC AND MONITORING SYSTEMS PRODUCED IN VÚJE, OKRUŽNÁ 5, 918 64 TRNAVA, SLOVAK REPUBLIC

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Abstract

Based on the 20 years experience in on-line vibration diagnostics of mechanical components in the primary circuit of nuclear power plant PWR WWER-440, VÚJE, Okružná 5, 918 64 Trnava produces its own diagnostic and monitoring systems since 1990. The variety of diagnostic systems includes: loose part monitoring system (LPMS), monitoring system of main circulating pumps (MCPMS), vibration monitoring system (LVMS), leakage monitoring system (LMS). The emphasis in the hardware solution is put on the design modularity and versatility so that many subcomponents (circuit boards) are common or highly similar for all systems. Using exclusively digital data for processing enhances the reliability of the measurements and allows the easy data transportation from one computer to another (e.g., for more sophisticated analysis). Trends in the software development follow the similar path as for the hardware solution - namely, the modularity and versatility of software is the imperative goal. The modern operating systems also incorporate the ability of network communication, which is crucial for the integration of stand-alone diagnostic systems into nuclear power plants information system. So far a number of systems have been successfully installed: 6 LPMSs (Jaslovské Bohunice, Dukovany), 4 MCPMs (Jaslovské Bohunice) and 2 LVMSs (Jaslovské Bohunice), all systems operate in PWR WWER-440 environment. Another diagnostic systems are under construction: 2 LPMSs (Temelin, PWR WWER-1000), 2 MCMSs (Mochovce - PWR WWER-440) and 2 LMSs (Jaslovské Bohunice).

1. INTRODUCTION

Based on the 20 years experience in on-line vibration diagnostics of mechanical components in the primary circuit of nuclear power plant PWR WWER-440, VFJJE, Okru2nd 5, 918 64 Trnava, SLOVAK REPUBLIC produces its own diagnostic and monitoring systems since 1990. The variety of diagnostic systems includes:

a) the loose part monitoring system (LPMS),
b) the monitoring system of main circulating pumps (MCPMS),
c) the loop vibration monitoring system (LVMS),
d) the leakage monitoring system (LMS).

The common hardware solution for all systems mentioned above consists of the following components:

i/ the sensors, which are specific for each system (e.g., piezoelectric accelerometers, humid sensors).

ii/ preamplifiers,
iii/ iii/isolated amplifiers integrated with analog/digital (A/D) converters and low-pass/high-pass (LP/HP) digital filters,
iv/ digital (PC-based) unit for the data processing, storage, retrieval and presentation.

All components - except the sensors and the personal computer - are produced by VCJE Okru2nd 5, 918 64 Trnava.

The emphasis in the hardware solution is put on the design modularity and versatility so that many subcomponents (circuit boards) are common or highly similar for all systems. Using exclusively digital data for processing enhances the reliability of the measurements and allows the easy data transportation from one computer to another (e.g., for more sophisticated analysis).

Trends in the software development follow the similar path as for the hardware solution - namely, the modularity and versatility of software is the imperative goal. In our opinion, another important feature is the use of up-to-date multitasking operating systems (like OS/2 from IBM or Windows NT or 95 from Microsoft) in diagnostic systems. Indeed, at least for LPMS, such an operating system is the necessity because the continuous monitoring of all measurement channels -must be provided in the background regardless to the operator activity in the foreground (e.g., detailed data analysis on the same computer). The modem operating systems also incorporate the ability of network communication, which is crucial for the integration of stand-alone diagnostic systems into nuclear power plants information system.

Up to now we have successfully installed 6 LPMSs (Jaslovské Bohunice, Dukovany), 4 MCPMs (Jaslovské Bohunice) and 2 LVMSs (Jaslovské Bohunice), all systems operate in PWR WWER-440 environment. Another diagnostic systems are under construction: 2 LPMSs (Temelin, PWR WWER-1000), 2 MCMSs (Mochovce - PWR WWER-440) and 2 LMSs (Jaslovské Bohunice).

2. LOOSE PART MONITORING SYSTEM (LPMS)

LPMS is constructed for the detection, localization and mass estimation of loose parts which can be possibly found in the primary circuit of nuclear power plant (NPP).

According to the technical norms (i.e., DIN 25475, USNRC RG 1.133), this system has to detect a loose part which is localized 0.91 meters from the sensor and its kinetic energy is 0.68 J. The proposed system meets these requirements. All parts of the system meet the relevant technical norms in Czech Republic and Slovak Republic.

Work conditions for the components which are installed in the hermetic zone of NPP (preamplifiers, impulse hammers) are as follows:

- - operational temperature: 65 degree C long term, short term limit of 93 degree C;
- - absolute pressure: 0.085 to 0.103 MPa long term, 0.5 Mpa short term;
- - relative humidity: up to 90 % long term;
- - radiation dose: 0.5x10- 3 grays/hr.

LPMS works in full autonomous regime and is conceptually made in modular form with regard to the hardware and software. It is possible to connect LPMS with other diagnostic systems or with the information net of NPP.

2.1 Hardware components of LPMS

The measurement chains contain sensors (accelerometers) and preamplifiers. The accelerometers are installed in the chosen locations of the primary circuit where there is the highest probability that loose parts will occur - e.g., the bottom of reactor vessel, the hot input and cold output of primary water to and from the reactor, respectively, hydraulic part of main circulating pump, the input and output chambers of steam generator. Typically, about 20 ~ 24 sensors are used for one unit of NPP WWER-440 or 1000.

The analog signals go at first through isolated amplifiers. After their amplifying, they are digitalized and filtered on the card of Digital Signal Processors (DSPs). A/D converters have 16 bits with an anti-aliasing property and a flat frequency response from 0.5 kHz to 20 kHz. Two signals can be simultaneously viewed on the oscilloscope. The right channel goes automatically to the loudspeaker and can be checked by hearing. The combination of two signals can be chosen directly by user from programme without suppression of any system function.

The special signal processor with the rapid transient memory is the "heart" of LPMS. It enables the parallel measurement of maximum 32 signals and has the internal possibility of programming the trigger threshold for each channel separately, which is derived from the short-time RMS value. By the periodical overwriting of trigger threshold, the change of underground noise can be accepted. The segmented ring memory consists of 6 blocks for 6 bursts. The number of data samples for each channel in each memory block depends on the number of channels. For 8, 16, 32 channels one has 32768, 16384 or 8192 digital data samples for each channel in each of 6 memory blocks, respectively.

After the trigger threshold is reached for an arbitrary channel in the actual memory block, the burst is recognized and the collection of digital data is ended in this memory block (the length of data pre-acquisition before the start of burst is programmable). The measurement continues practically immediately in the subsequent memory block. The previous memory block can be transferred in the main/extended memory of the PC and processed and/or archived. The so - called "dead time" of impulse processor (i.e. the time when the impulse processor cannot monitor the channels for the existence of burst) is zero.

The control unit of LPMS is constructed with the utilization of industrial grade computer AT 586. The basic configuration includes 16 MB RAM (expendable to 32 MB), dual 210 MB hard disk (minimum), floppy disk 3 1/2" (1.44 MB) minimum, mouse pointer, industrial grade SVGA 640 x 480 minimum, colour monitor 15", industrial grade AT keyboard, standard serial port RS 232 (2) and parallel port Centronics (1), optical disk backup, Ethernet card for the network communication, multitasking operating system IBM OS/2 Warp and the utility software for diagnostics and optical disk backup.

The generator of calibrated signal is the source of exactly defined signal which serves for the calibration and the verification of each of measurement chains including the sensor (integrity test). The following parameters of calibrated signal are programmable: the form of signal (impulse, sinusoidal, random noise), the amplitude (in the range from 0.1V to SV) and the frequency (from 1 Hz to 20 kHz). The protocols can be made which document the frequency response of the measurement chain under consideration.

It is usual to install one impulse hammer in the cold leg of each loop in NPP. This impulse hammer represents an independent instrument for the verification of LPMS' sensitivity (module test). The bursts with kinetic energy from 0.1 J to 1.0 J are full programmable by the user. The functional block diagram of LPMS is depicted on Fig. 1.

2.2 Software components of LPMS

The user software of the LPMS is written in WATCOM C++ language under the multitasking operating system OS/2 Warp. Its purpose is:

- to detect automatically loose parts that weight between 0.11 kg to 13.6 kg with an energy of 0.68 J or greater within 0.91 meters of an accelerometer;
- to provide the localization of a loose part source based on the dispersion of stress waves in metallic primary circuit within +/- 0.25 meters using linear models of the reactor vessel and piping system;
- to provide a method of determining the loose part weight with a range of 0.2 kg to 5 kg with a resolution of 0.2 kg based on the Hertz's theory of elastic impacts.

The user software consists of individual processes which can work and communicate asynchronously in the operating system OS/2. Due to the multitasking property of OS/2 the processes do not disturb the continual acquisition of data from LPMSI measurement chains.

3. MONITORING SYSTEM FOR MAIN CIRCULATING PUMPS (MCPMS)

MCPMS is designed for the quasi-continual monitoring of mechanical status of main circulating pumps in the primary circuit of NPP. The monitored processes include the bearing failures and degradation, vibrations excited by the rotational parts in the driver, hydraulic part and couple, vibrations excited by the interactions of electromagnetic forces in an inductive motor, cavitation, failures of sealing blocks and the slow movements of MCP as a rigid body.

The technical means for MCPMS are similar to those for LPMS. Of course, there are some modifications, which follow from the different physical processes involved in the monitoring of MCPS. For example, the accelerometers are used also in the low frequency range from 1 Hz to about 10 - 15 kHz. For the monitoring of cavitation the ultrasonic sensors are used in the frequency range from 50 kHz to 400 kHz. As option, the shaft vibration transducers are provided.

The hardware block diagram is similar to the Fig. 1. The block of DSP computes also the single and double integration from digital data of acceleration to analyze the velocity and displacement signals, too.
MCPMS is working in the autonomous regime with the possibility of definition of time periods between measurements, i.e. quasi-continuously. The diagnostic parameters are computed from the time domain and frequency domain, and are compared with the reference -measurements. The special tests - such as signal analysis procedures, trend evaluation, statistics, etc. - are available under the operator control.

4. LOOP VIBRATION MONITORING SYSTEM (LVMS)

The system is designed for the periodic or repetitive realization of diagnostic vibration tests, mainly in the low frequency range (up to 100 Hz). The monitored objects are components of NPP coolant loops. The subject of attention are their vibration behaviour and their own nodal properties. The main task is to detect and prevent an excessive dynamic load with the high-cyclic fatigue and changes or failures in the placing of main loop components. LVMS is capable to co-operate with the diagnostic system for intra-reactor diagnostics and neutron noise analysis.

The measurement chains include sensors for relative and absolute displacement, sensors for the coolant pressure fluctuations and possible outputs from other diagnostic systems.

From the methodological point of view, the block of DSP computes auto- and cross-spectra of all signals in parallel with sampling. The identified spectral peaks are monitored in regard to their amplitudes and frequency shifts. The software enables the detailed analysis of various statistics and trends. All analysis results are archived and can be documented in hard-copy form.

5. LEAKAGE MONITORING SYSTEM (LMS)

LMS (called also HUMON = Humidity Monitoring) is designed for the continuos humidity monitoring in the hermetic zone of NPP. It is one of three independent monitoring systems, which are required by Nuclear Regulatory Commission in Slovakia for all NPPS.

It works autonomously and provides the localization of leakage in the primary circuit; this information serves as the first caution before the integrity failure of primary coolant piping.

LMS meets the criteria defined for the leakage monitoring before the integrity failure (LBB = Leak Before Break). The international qualification for the material of primary circuit in NPP WWER-440 is to detect the leakage from 4 litres per minute in the time interval one hour from its origin. LMS consists of two parts which communicate via serial links: the measurement unit and the processing unit. The measurement unit consists of the pneumatic part and the electronic part.

The pneumatic part provides the air supply into the measurement chambers and its return into the box of steam generators. It also controls the switching between the measurement chambers for measurement chains and the source of air with defined humidity (humidity filter).

The electronic part provides the measurement of absolute humidity, data pre-processing and data sending to the processing unit, the control of electromagnetic valves and the communication with the processing unit.

The processing unit is based on the personal computer IBM with standard peripheries; the recommended configuration consists of PC Pentium 75 MHz / 16 MB RAM / HD 850 MB / SVGA 800x600x256. The user software is provided under the operating system OS/2 Warp and enables:

- communication with the measurement unit (data concentrator);
- definition of parameters for humidity sensors (calibration, activity);
- definition of alarm threshold for each measurement chain;
- start / stop of measurement;
- test of measurement chains by operator;
- monitoring of all active measurement chains in digital and graphical forms and their archiving;
- statistics over archived data (e.g., the average over defined time interval);
- control of external relay for remote alarm;

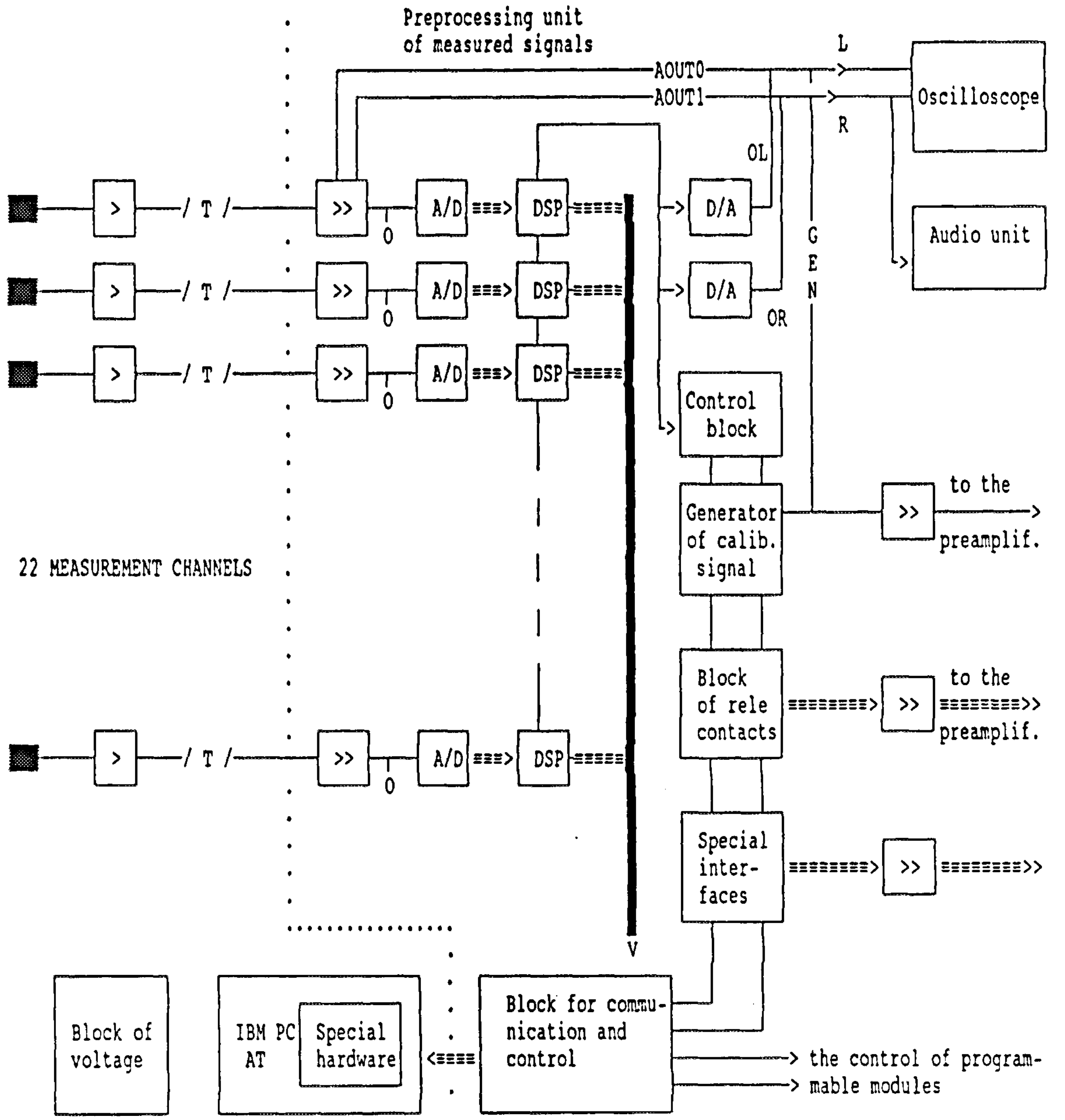
- detailed documentation of measured and/or archived data by hard-copy or by the export of results into file;
- support of diagnostic network in NPP.

The measurement unit can work in the autonomous regime. In the case of PC failure the measurement unit is capable to store the data measured with one minute period in its own local memory for at least three days. After the PC restart the data are read from the measurement unit and processed in usual way.

6. CONCLUSION

VFJJE has been dealt with the NPP diagnostics for 20 years up to now. The substantial amount of deliveries and services concems the NPP in Jaslovské Bohunice, but there are considerable activities for NPP Mochovce, Dukovany and Temelin, too. The needed results are not only of type of research support, but mainly of type of technical and operational support. Significant activity is the delivery of the whole diagnostic systems with assuring of projecting, mounting and introduction into the operation.

Fig.1 HARDWARE BLOCK DIAGRAM OF LPMS



The meaning of symbols:

sensor	—/ T /—	connection through ther-mozone	DSP	digital signal processor		Note:
> charge preamplifier	>>	isolated amplifier	A/D	block of di-gitalization		For the case of clarity, there are no controled and voltage signals of program-mable modules visualized.

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Session 3
Impact on Performance and Safety

SESSION 3

IMPACT ON NPP PERFORMANCE AND SAFETY

Chairpersons: Mr. U. Südmersen, Germany
Mr. D.W. Anderson, U.K.

XA9743529

Data Fusion and Sensor Management for Nuclear Power Plant Safety

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1 Introduction

The data obtained from sensors in a nuclear power plant (NPP) provide the essential information source for control and protective systems and operating personnel. The information processing is getting more and more sophisticated due to increasing automation and implementation of modern technologies together with appropriate integration. By means of this, variety of tasks are performed in accordance with their design requirements. The availability of large volume of sensors is beneficial not only for providing a greater volume of information but also providing information in depth. However the increase of number of sensors brings the problem of sensor management for effective information acquisition as well as sensor/data fusion for effective information extraction. The role of computerized operator support systems in nuclear industry is getting increasing gravity. In parallel with this gravity the high reliability of vast information being used in such support systems must be maintained. An essential tool for this goal is data/sensor fusion and sensor management. Such an approach is closely related to verification & validation process which is also a must as a panultimate approval before such systems being put into operation as sharing the task of the nuclear power plant operator under his/her supervision.

The paper describes the implementation of the data-sensor fusion and sensor management technology for accident management through simulated severe accident (SA) scenarios subjected to study. By means of accident management the appropriate prompt actions to be taken to avoid nuclear accidents is meant, while such accidents are deemed to somehow be imminent during plant operation. The organisation of the present paper is as follows. As the data-sensor fusion and sensor management is an emerging technology which is not widely known, in Sec. 2, the definition and goals of data-sensor fusion and sensor management technology is described. In Sec. 3 first, with reference to Kalman filtering as an information filter, statistical data-sensor fusion technology is described. This is followed by deterministic data-sensor fusion technology using gross plant state variables and neural networks (NN) and the implementation for severe accident management in NPPs. In Sec. 4, the sensor management technology is described. Finally, the performance of the data-sensor fusion technology for NPP safety is discussed.

2 Data-sensor Fusion and Sensor Management Technology

The data measured by the NPP sensors provide essential input for the control and protective systems and for the operating personnel. By means of the modern advanced techniques in hardware and software the reliability of data acquisition and processing is enhanced. These advanced techniques are applied during normal operation and they can avoid serious sensor malfunctions of the data collection and processing systems and thereby reducing the incident frequency or mitigating the consequences of incidents. By increasing the confidence in validity of the measured signals, a higher reliability can be obtained so that the plant operating conditions comply with the safety standards. Also by the replacement of the incipiently failed sensors the unplanned trips could be avoided. Sensors can provide many kinds of information about the plant operation

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which can be used by autonomous mechanisms in variety of means in the performance of a variety of tasks.

The availability of multiple sensors is beneficial not only in providing a greater volume of information but also increasing in breadth. The broad base of information provided by different sensing modalities and indirectly, from the synergistic combination of two or more pieces of data. Increasing the breadth of information, however, is not the only benefit of multiple sensing; a redundancy of information is also important. Redundant information ensues not only from multiplicity of identical sensors but also from multiple sensors which differ in their method of operation which ultimately provide the same information.

The availability of redundant information sources is beneficial in providing for choices among various sensing strategies when information must be actively sought, as in the case accident conditions. In addition, if a sensor becomes defective, failing completely, then management can continue if other means of acquiring information is available. Because sensor measurements are seldom perfect, another advantage to the use of redundant information provided by multiple sensors is that it allows measurement errors to be offset by comparing and combining measurements. If sensory information proves inconsistence due to noise component in the measurement, then some form of averaging can be used to provide better estimates. When a piece of data differs significantly from what was expected by other measurements, then sensor failure may be indicated and that datum can be rejected.

The availability of multiple sensors can thus extend the capabilities of autonomous mechanisms in addition to allowing for more reliable and cost effective plant operation and management. However, along with these benefits comes a great need to coordinate the sensors and to organize the flow of information. This systematic coordination is called data/sensor fusion. In the case the data are obtained from measurements which is the case under consideration in this paper, the sensors are naturally associated with the measurement so that data-sensor fusion is considered together although the general treatment requires the data fusion and sensor fusion separately. In relation to data and sensor fusion technologies, the following explicit definitions can be stated. *Data fusion* is the process by which data from a multitude of sensors provide an optimal estimate of a specified status in a nuclear power plant. This is achieved by synergistic combination of information from the information and knowledge sources. *Sensor fusion* is the process of combining multiple measurements from sensors into a single measurement for a reliable estimate. *Sensor management* is the selection of sensing strategies among other alternative strategies for effective information acquisition.

3 Data-sensor Fusion

3.1 Statistical Data-sensor Fusion: Kalman Information Filter

To achieve goals of data-sensor fusion described in the preceding section, initial processing of sensory information and accurate state estimation is imperative before further information processing takes place. The pre-information processing requires probabilistic descriptions due to the randomness of the measurement errors as well as the noise sources driving the process where the process is represented by a stochastic model. To begin with, let

$$x = [x_1, x_2, \ldots, x_n] \tag{1}$$

be the state vector of the dynamic system. We assume that the observation vector is related to the state vector in the form of

$$x = f(z + \nu) \tag{2}$$

where z denotes the measurement vector and ν denotes the independent Gaussian random measurement errors which are additive. By means of series expansion the above model is approximated as

$$x = f(z) + J\nu \tag{3}$$

where J is the Jacobian matrix of the function f with respect to z. Hence the uncertainty involved becomes

$$J\,E[\nu\nu^T]\,J^T \tag{4}$$

where $E[\nu\nu^T]$ is the covariance matrix of the noise ν. The singular value decomposition of the $J\,E[\nu\nu^T]\,J^T$ matrix is given by

$$J\,E[\nu\nu^T]\,J^T = [R D R^T] \tag{5}$$

where R is an orthonormal modal matrix the columns of which are the eigen vectors of the covariance matrix of x. D is the diagonal matrix containing the eigenvalues. They represent the scalar variance in each direction corresponding to each of the components of x , the direction being determined by the unity eigen vectors in R. When all the directions are considered for a given state x, the geometrical boundary is an ellipsoid with principal axes determined by the eigen vectors. This is schematically represented in Fig. 1.

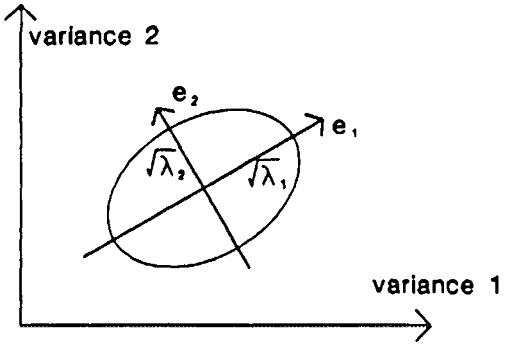

Fig. 1: *Uncertainty ellipsoid for a 2-dimensional space. e_1, e_2 are unit eigenvectors; λ_1, λ_2 are eigenvalues*

The aim of sensor-data fusion is to reduce the volume of the ellipsoid of uncertainty in the multidimensional space. To this end, several measurements are taken over time. We consider the measurements are in discrete time denoted by k. The set of observations up to time k is

$$Z_k = [z(1), z(2), \ldots, z(k)] \tag{6}$$

Hence the conditional probability density function of x is given by Bayes's theorem

$$p(x|Z_k) = p(Z_k|x)\,p(x)\,/\,p(Z_k) \tag{7}$$

which can be recursively calculated after each observation $z(k)$, of the form

$$p(x|Z_k) = \frac{p(z(k)|x)\,p(x|Z_{k-1})}{p(z(k)|Z_{k-1})} \tag{8}$$

From above, the information update for a single sensor system, in terms of log-likelihood, is given by

$$ln[p(x(k)|Z_k)] = ln[p(x(k)|Z_{k-1})] + ln[c\,p(z(k)|x(k))] \tag{9}$$

This is depicted in Fig. 2 where the sensor provides observations $z(k)$, $c = 1/p(z(k)|Z_{k-1})$. An observation model converts the observation as likelihood information which is added to the prior information accumulated through all preceding observations. Multi-sensor systems can be formed by combining above described single sensor systems.

The recursive state estimation by uncertain observations is given by Kalman filtering. The Kalman filter provides optimal estimations in the statistical sense. The Kalman filter equations are derived using a variety way of approaches [1,2]. An alternative formulation of Kalman filtering is in the form of information filter [3]. The information is related to the inverse of the covariance matrix and it is directly related to the Bayesian probabilistic information given above.

A linear stochastic system can be expressed in the form of a set of first order linear equations of the form

$$x(k) = A(k)\,x(k-1) + w(k) \tag{10}$$

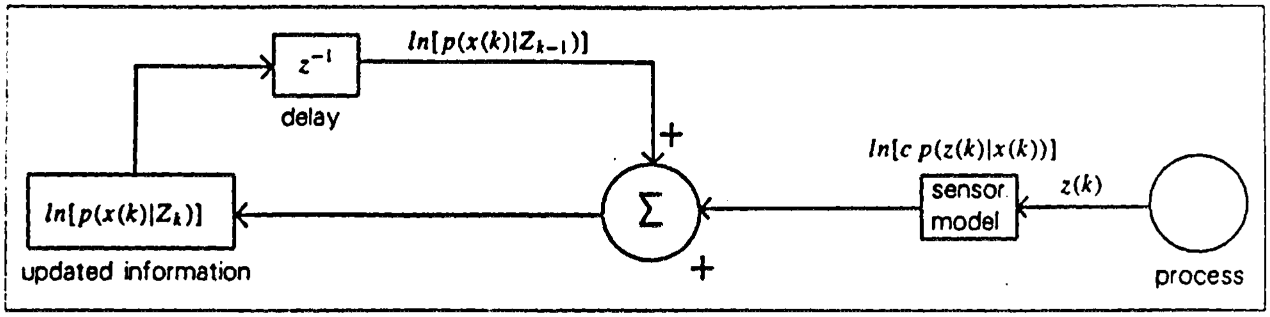

Fig. 2: *Single sensor information update*

and the measurement equation

$$z(k) = H(k)\,x(k) + v(k) \tag{11}$$

where $A(k)$ is the state transition matrix; $z(k)$, measurement vector; $H(k)$, observation matrix; $w(k)$ and $v(k)$ are process and measurement noise sources respectively which are Gaussian white and uncorrelated:

$$E\{w(k)\} = 0 \tag{12}$$

$$E\{w(k)\,w(j)^T\} = Q(k)\,\delta_{k,j} \qquad \forall k, j \tag{13}$$

and

$$E\{v(k)\} = 0 \tag{14}$$

$$E\{w(k)\,w(j)^T\} = R(k)\,\delta_{k,j} \qquad \forall k, j \tag{15}$$

The estimated state vector at the discrete-time k is given by

$$\hat{x}(k|k) = E\{x(k)|Z_k\} \tag{16}$$

with covariance

$$P(k|k) = E\{(x(k) - \hat{x}(k|k)(x(k)) - \hat{x}(k|k))^T\,|Z_k\} \tag{17}$$

Corresponding to this estimate, the newly defined vector $y(j)$ and its estimates $\hat{y}(j)$

$$\hat{y}(j) = P^{-1}(j)\,\hat{x}(j) \tag{18}$$

is called information state vector and the inverse covariance $P^{-1}(k|k)$ is called information matrix. The recursive computations become

$$\begin{aligned} P^{-1}(k|k) &= P^{-1}(k|k-1) + H(k)^T R^{-1}(k)\,H(k) \\ P(k|k-1) &= F(k)\,P(k-1|k-1)\,F(k)^T + Q(k) \end{aligned} \tag{19}$$

$$\begin{aligned} \hat{y}(k|k) &= \hat{y}(k|k-1) + H(k)^T R^{-1}(k)\,z(k) \\ \hat{y}(k|k-1) &= P^{-1}(k|k-1)\,F(k)\,P(k-1|k-1)\,\hat{y}(k-1|k-1) \end{aligned} \tag{20}$$

In the above formulation, the vector $H(k)^T R^{-1}(k) z(k)$ is a sufficient statistic of $x(k)$ [4]. The sufficient statistic comprises all the information contained in the observation. Therefore the vector $H(k)^T R^{-1}(k) z(k)$ is a model of the likelihood $p(z(k)|x(k))$. Using these recursive equations, the estimated state may be obtained from

$$\hat{x}(k|k) = P(k|k)\,\hat{y}(k|k) \tag{21}$$

Although the information filter equations given here are for a single sensor and the relevant recursive estimations correspond to data fusion through the accumulated measurements, the same form can be extended for multiple sensors and in this case the observations $z(k)$, observation matrix $H(k)$ and the measurement noise covariance $R(k)$ become

$$\begin{aligned} z(k) &= [z_1(k), z_2(k), \ldots, z_n(k)] \\ H(k) &= [H_1(k), H_2(k), \ldots, H_n(k)] \\ R(k) &= [R_1(k), R_2(k), \ldots, R_n(k)] \end{aligned} \tag{22}$$

Due to sensor/data fusion feature, an increasing number of Kalman filtering applications in NPP operation are performed and they are reported in the literature [5,6].

3.2 Deterministic Data Fusion Technology: Neural Networks

3.2.1 Neural Network

In the last decade, research on artificial neural networks has progressively became a popular research field. The more recent growth of interest in artificial neural networks seems to be caused by their promise to yield solutions that traditional approaches do not yield. A typical feedforward neural network structure is shown in Fig. 3 and a brief description is as follows [7].

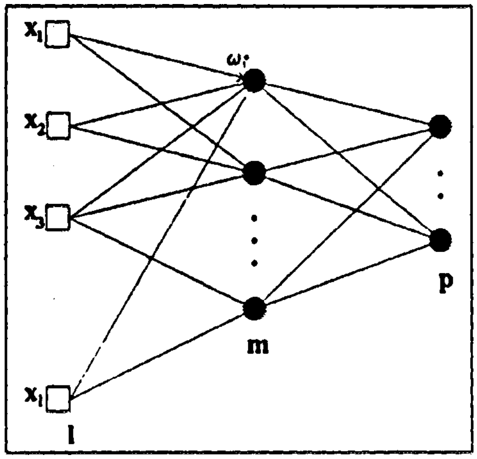

Fig. 3: *A feedforward neural network structure with l input signals, m hidden and p output neurons, ω is the weighting factor.*

In Fig. 3 each circular node is called neuron or perceptron. The network has l-input signals, m-input neurons, p-output neurons and it may have a number of hidden neurons. Such a network can be considered as a function from $\mathbf{R}^l$ to $\mathbf{R}^p$ where R is a set of real numbers. The simplest network structure has only input and output neurons where input neurons correspond to the signal sources. We can consider such a network for simplicity without affecting the general case. Speaking in terms of input and output signals, in a feedforward network the signals propagate only in one direction. Input to the network provide the arguments of the network function F so that the l-input signals generate the vector $x = (x_1, x_2, \ldots, x_l)$. The output neuron p generates the value y. Together, the p-output neurons generate the p-vector $y = (y_1, y_2, \ldots, y_p)$. Hence, the neural network performs the task of calculating the value of the output vector y from the input vector x. We can represent this by

$$\{F : S \longrightarrow \mathbf{R}^p \mid S \in \mathbf{R}^l\} \tag{23}$$

The input signals and the input neurons are associated with weights w and so are the output neurons with the input neurons. Concerning one of the input neurons, the transfer function between its input and output can be represented by

$$f(x_1, x_2, \ldots, x_l) = \sigma\left(\sum_{i=1}^{l} w_i x_i + \Theta\right) \tag{24}$$

where Θ, is called threshold and the function f, σ are often called the activation function. $\underline{w}.\underline{x}$ is the standard inner product on $\mathbf{R}^p$. In the same way, the output of the network can be represented by

$$\underline{y} = \underline{H}(\underline{w}.\underline{x} + \Theta) \tag{25}$$

where $\underline{y}$ is the output vector and $\underline{H}$ is the vector representing p activation functions. $\underline{w}.\underline{x}$ is the inner product on $\mathbf{R}^l$.

During the training of a feedforward neural network we assume a network architecture with m-inputs and p-outputs is given. In addition, we assume a fixed function $G : \mathbf{R}^l \leftrightarrow \mathbf{R}^p$ is given. Then the learning process is an adaptive process which keeps adapting the values of the weights and thresholds until the resulting network function F is approximately equal to G.

3.2.2 Data/Sensor Fusion

The learning process during a neural network training is a stochastic process[7]. To see this, consider a vector x of independent variables and a scalar d which is independent variable. If we have N measurements of x, we have $x_1, x_2, \ldots, x_N$ and correspondingly $d_1, d_2, \ldots, d_N$. The neural network model is expressed by

$$d = g(x) + c \tag{26}$$

where $g(x)$ is some function of the vector x and e is random expectational error. In this model, the function $g(x)$ is defined by

$$g(x) = E[d|x]. \tag{27}$$

The conditional expectation defines the value of d that will be realized on the average given a particular realization of x. Let the actual response of the network be defined by

$$y = F(x, w) \tag{28}$$

where w represent the synaptic weight vector. The synaptic weight minimization for the cost function

$$J(w) = E[(d - F(x, w))^2] \tag{29}$$

would also minimize the multiple integral

$$E[(g(x) - F(x, w))^2] = \int f(x)\,[g(x) - F(x, w)]^2\,dx \tag{30}$$

where $f(x)$ is the probability density of x. This result indicates the statistical nature of the learning process even though the different patterns of a particular realization of x are deterministic. From the probability theory viewpoint, the input-output pairs of x used for the training obey an arbitrary distribution $f(x)$ and therefore do not take functional relationship between input and output deterministically. $f(x|w)$ being the density function parameterized by w, the model $f(x|w)$ with good generalisation capability should approximate the true distribution $f(x)$. The log likelihood is expressed by

$$L = log f(x|w) \tag{31}$$

so that, N times the expected log likelihood parameterized by w is defined as

$$N\,E[log f(x|w)] = N \int f(x)\, log f(x|w)\, dx \qquad (32)$$

as an information measure for the sensor/data fusion and information accumulation after the learning process.

Due to sensor/data fusion feature, an increasing number of neural network applications in NPP operation are performed and they are reported in the literature [8,9]. Some severe accident m...agement applications are presented in this this study.

3.2.3 Sensor Management

Sensor management is making decisions with respect to alternate estimation strategies. The data fusion methodology described above for state estimations can be performed in different ways using the most appropriate sensory infonnation. From these measurements the state of the process is estimated in accordance with some optimality criterion.

In the Kalman filtering approach, this is done by checking whether the residuals indeed possess their statistical properties. That is, the Gaussian process noise variance is expected to be [5]

$$R'(k) = Z(k) - H(k)x(k|k-1) \qquad (33)$$

$$E[R'(k)R'(k)^T] = H(k)P(k|k-1)H(k)^T + R(k) \qquad (34)$$

where $\mathbf{R}(k)$ is the variance of the Gaussian-white process noise. From the preceding equation we are able to judge whether or not the mathematical model satisfactorily describes the real system behaviour.

In the neural network approach, the sensor management can be performed according to the decision making based on hypothesis testing approach [11] or the expected log-likelihood function

$$N\,E[log f(x|w)] = N \int f(x)\, log f(x|w)\, dx \qquad (35)$$

4 Data/Sensor Fusion Application with Neural Networks

The deterministic data fusion technology using the gross plant state variables of stochastic model makes use of a set of NNs of feedforward type in the form of Multi Input Single Output (MISO) [12]. Each network is devoted to one process signal where the network is made insensitive to that process signal. Each individual network is driven by stochastic signals and trained by Kalman filtering for appropriate knowledge acquisition. The outputs from the neural networks indicate failures in the system immediately and progressively so that a basic rule based decision making identifies the failing sensors, component or components as well as sequence of failing information using an M-out-of-N logic.

Deterministic information processing involves two approaches. In the first approach, similar to the stochastic information processing by neural nets, a set of neural networks is used in the form of MISO as described above. The outcome of the networks are evaluated by means of M-out-of-N logic where actual plant signals from the sensors are used for failing component identification in a distributed subsystems environment (core, pressurizer, steam generators etc.). The MISO structure and the associated failure detection and diagnostic logic is illustrated in Fig. 4.

Dynamic behaviour of Borssele NPP has been investigated with the MISO failure detection system where the neural network output is the steam generator water-level signal (SG2WL). The neural network estimator together with the failed sensor response is indicated below, where it is seen that false water-level indication is compensated by correct neural network estimate as shown by dotted line (see Fig. 5.). The correct estimation prevails relatively short (6 s) due to scram but time is long enough to take action to avoid an unnecessary scram.

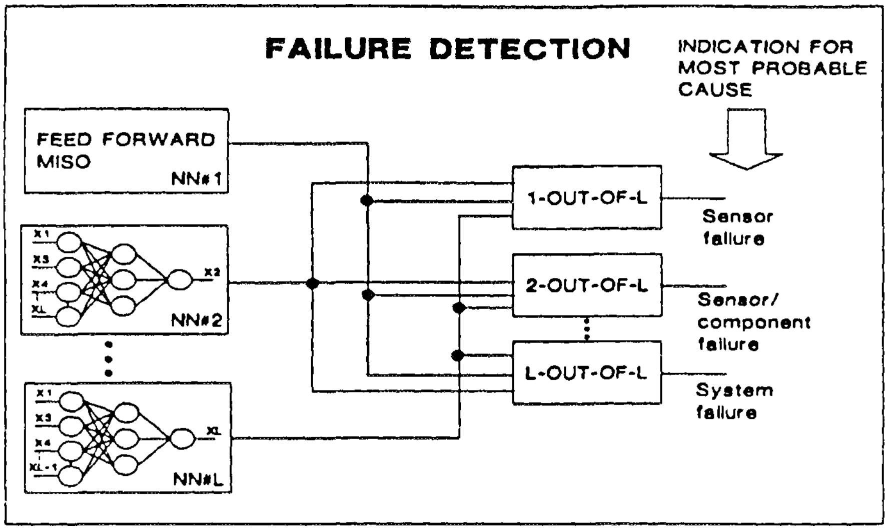

Fig. 4: *The MISO structure and failure detection structure*

In the second approach for deterministic information processing selforganizing neural network with selective information at the input, is implemented. Accordingly, enhanced generalization capability applied to various severe accident cases is exercised. Here, the plant's information are introduced to the inputs of the network sequentially and no supervised output is specified. Input information contains normal operation as well as various severe accident situations. As the number of patterns to train the network is rather high, selforganizing network is used for the selection of the representative patterns for each accident scenario. The representative patterns become known by corresponding cluster centers formed during the network's training.

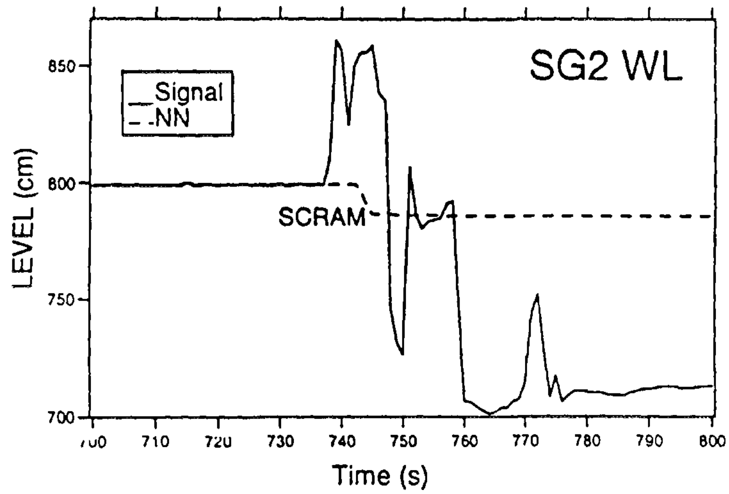

Fig. 5: *Fast sensor failure estimation by neural network for steam generator water level signal*

Following the selforganizing network where severe accident as well as normal operational pattern information reduction is accomplished, a second neural network is used as a supervised network for the immediate identification of the accidents for which management is aimed.

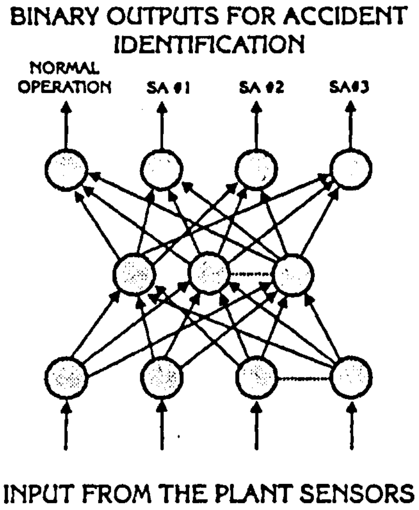

Fig. 6: *Severe accident identification and normal plant operation indentification by neural network.*

The supervised neural network has binary outputs each of which is assigned to one of the accidents in the set of designed severe accident (SA) scenarios. The training having been accomplished by the patterns, the network is driven by the inputs from the plant sensors in real-time operation. The normal operation is also indicated by one of the binary outputs during plant operation. Severe accident situations are created by simulation work using RELAP-5 code. RELAP is developed for the analysis of the thermo-hydraulic system behaviour of light-water cooled nuclear fission reactor transients and accidents. Three simulated SAs are considered:

The first SA scenario is anticipated transient without scram (ATWS) in the form of loss of feed-water with failed emergency cooling water system leading to failed reactor scram caused by low water level in the steam generator (RESA) and this is followed by turbine isolation (TUSA) where at t=100 s steam generators dried-up and at t=600 s void formation in the reactor core started. The scenario continued until t=1675 s where reactor core completely dried-up.

The second SA scenario is a cold-leg break with area of 120 sq. cm. At t=0 s cold-leg break is identified and t=2.3 s RESA signal is initiated due to boiling margin followed by TUSA where in the scenario no action is taken for cooling. In the secondary system only one emergency feed-water pump is working for feed-water. The cooling at the secondary side is 100 K/hr until the main steam valves are closed. At t=9.6 s both main cooling water pumps are failed and at t=12.3 s emergency feed water started. At t=1086 s main-flow valves are closed. The core tends to melt after 1500 s.

The third SA scenario is the station blackout. Initially there are main coolant pumps and feedwater pumps failures, no emergency feedwater and no TJ-injection at t=0 s, leading to TUSA. At t=0.76 s pump speed lowered lower than 145.108 rad/s so that RESA is initiated. At t=4250 s steam generators dried-up, t=5847 s core boiling started and t=9090 s fuel cladding temperature reaches above 1500 K. At t=9772 s, fuel cladding temperature became above 2100 K which led to core melt.

These three scenarios together with the normal operational data are set into above described hybrid neural network system, that is coupled neural networks trained by both self organization and supervisedly afterwords, by turn. The SA identification as well as normal operation identification are satisfactorily exercised by the above described simulation data from the scenarios and normal operational data from the NPP.

5 Discussion and conclusions

With respect to NPP reliability and safety, data/sensor fusion and sensor management technology plays important role. By means of this technology the right decisions are performed during normal operation as well as in the case of management of accidents. Kalman filtering is an optimal estimator for recursive state estimation which permits sample by sample real-time implementations. However, this paper explicitly takes another view, pointing out such a filter works as an information filter providing Fisher's information measure which gives a measure of the amount of information about the state vector inherent in the observations. In other words, it provides the essential tool of modern state-space model sensor/data fusion technology. The information is provided by the inverse covariance matrix which can be used in variety of ways. For instance, to determine the error ellipsoid for decision-making. The nonlinear form of Kalman filtering is known to be as *extended Kalman filtering* the information filter form of which can be obtained in a similar form. In addition to the sensor/data fusion properties, due to its several other desirable features, Kalman filtering utilisation in NPP operation is an indispensable auxiliary tool for optimal operational decisions.

The counterpart of the nonlinear stochastic modeled data/sensor fusion is the *nonlinear black-box model* of the plant with gross plant signals, i.e., state variables. Here the neural networks are important functional tool for sensor/data fusion for safety related enhanced reliable plant monitoring as well as to cope with the critical situations.

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CANADIAN CANDU* PLANT DATA SYSTEMS FOR TECHNICAL SURVEILLANCE AND ANALYSIS

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ABSTRACT

Plant data systems are emerging as a critical plant support system technology. In particular, plant-wide Historical Data Systems (HDS) are pivotal to the successful implementation of technical surveillance and analysis programs supporting plant operations, maintenance, safety, and licensing activities. In partnership with Canadian CANDU utility and design organizations, AECL has conducted a review of current Canadian CANDU HDS approaches with emphasis on understanding the existing functionality and uses of plant historical data systems, their future needs and benefits. The result is a vision of a plant-wide HDS providing seamless access to both near real-time and historical data, user tool-kits for data visualization and analysis, and data management of the large volume of data acquired during the life of a plant. The successful implementation of the HDS vision will lead to higher capability and capacity factors while minimizing Operations, Maintenance, and Administration (OM&A) costs.

1. INTRODUCTION

As the operating environment of Canadian CANDU stations mature, there is a much greater awareness of the increasingly important role of various plant information systems and how they impact the overall effectiveness and efficiency of station operations. Operational experience with existing plant data and information systems, and how they impact all aspects of plant operations is enhancing this understanding. As a result, plant-wide historical data systems are emerging as a critical information technology supporting plant operations, technical surveillance, predictive and preventative maintenance, and plant safety and licensing programs aimed at increasing plant safety, availability, and performance while lowering overall OM&A costs. Substantial benefits are foreseen in the use of HDS technology. The integrated and effective use of plant data is vital to reducing cost, avoiding unnecessary or unplanned outages or equipment failures, and optimizing all aspects of operations and maintenance. Plant-wide HDS technology supports these improvements through:

- reduced manual effort in data acquisition,
- increased reliability, timeliness, and accessibility of data,
- improved ability to correlate data from several sources,
- enhanced capability for data visualization and analysis,
- improved efficiency in reporting and the distribution of information,
- reduced effort in performing post-incident analysis,
- improved detection and avoidance of problems, and
- improved planning and coordination.

These benefits directly support plant operational improvement in key program areas such as:

- plant performance monitoring aimed at increasing plant availability, thermal and electrical efficiency, capability and capacity factors,

* CANadian Deuterium Uranium

- safety and licensing programs in support of regulatory compliance monitoring and safety analysis, and
- predictive and preventative maintenance programs including Condition Based Maintenance (CBM) and Reliability Centred Maintenance (RCM) programs.

In partnership with Canadian CANDU utility and design organizations, AECL has investigated the current CANDU HDS implementations and issues, developed generic HDS requirements, and established requirements and recommendations for PC-based tools in support of technical surveillance and analysis. The result is a vision to provide a flexible and expandable HDS environment that meets a wide range of data integration, data management, data archival and retrieval, data visualization and analysis, and reporting and storage requirements in support of potential HDS uses. This paper describes current Canadian CANDU HDS implementations and issues, presents a model for HDS implementations including generic HDS requirements, and identifies opportunities and benefits of adopting HDS systems.

2. REVIEW OF EXISTING CANDU PLANT DATA SYSTEMS

Over the past several years, Canadian CANDU stations have focused their efforts on the development of Digital Control Computer (DCC) gateways and data servers to get data out of the control room and into the hands of engineering services and technical unit staff. A priority has been placed on providing reliable and easily accessible data on-line to a wide range of end-users to improve technical surveillance of the plant outside of the control room, and relieve control room operators from the task of manually collecting process readings. This has led to the development of data systems that acquire and store data from the DCC's and other data sources, and provide access to the data from any desktop computer on the station Local Area Network (LAN). Generically, these systems fit the definition of a plant-wide HDS although in some cases their historical data capability is limited. In general, the current station HDS implementations consist of:

- interfaces or gateways to acquire plant process data from the DCC (and possibly many other sources),
- a means of managing and storing the data, and of providing remote network access to the data, and
- tools to extract, visualize, and analyze the data on the user's personal computer (PC).

The observations made during the plant data systems review indicate that each CANDU station has taken an unique approach in developing its systems and they are at various stages of development and implementation. This is not surprising, since plant data system development at each station has occurred at different points in time and according to different requirements and constraints. Key factors affecting each development effort include:

- a balance between short-term, medium-term, or long-term requirements,
- a trade-off between budget, development schedule, and functionality,
- available in-house resources, and
- technology options and constraints at the time of development.

The Bruce NGS (Ontario Hydro) has developed the Plant Status Monitoring System (PSMS) for use on Bruce A (Units 1-4). PSMS is a client-server system that serves real-time data to desktop applications for use outside of the control room. The intent of the PSMS was to emulate real-time control room displays and provide easy access to historical process data over the LAN for the purpose of technical surveillance and analysis. Desktop user applications have been developed using LabWindows from National Instruments. Bruce B (Units 5-8) has not yet implemented an HDS, however, requirements have been written and the station is in the process of procuring and installing a commercial off-the-shelf HDS system.

The Darlington NGS (Ontario Hydro) HDS implementation, known as the Process Data Distribution System (PDDS), provides desktop access to archived DCC data. The system consists of a file server capable of storing up to four weeks of DCCX data and ten days of DCCY data, which is time-stamped and synchronized with a satellite time signal. There is no gateway connection to the DCC's. Each day, data is dumped from the DCC's to magnetic tape, then transferred from the magnetic tape to flat files on the file server, and later archived to optical disk. Data can then be extracted for use within standard desktop spreadsheets and word processors. There is no access to real-time or near real-time data outside of the control room.

The Pickering NGS (Ontario Hydro) HDS functionality is provided by the Data Extraction System (DES), with separate implementations for Pickering 'A' (Units 1-4) and 'B' (Units 5-8) [1]. The original function of the DES was to provide near real-time monitoring displays for the Authorized Nuclear Operators in the control room and within the Pickering Emergency Response Centre (PERC). Limited access to historical DCC data is also provided by the system. The system design is based on the use of off-the-shelf industrial Supervisory, Control and Data Acquisition (SCADA) software implemented within a PC environment (see Figure 1). In each DES, a SCADA PC receives data from the DCC's through a gateway PC. View Station PC's continually receive real-time process data from the SCADA PC over a dedicated control room LAN to drive advanced graphic displays in the control room. Both the SCADA and View Station PC's run FIX DMACS software, an industrial PC-based SCADA software package. Historical data access and near real-time data broadcasts for use outside of the control room are currently being implemented.

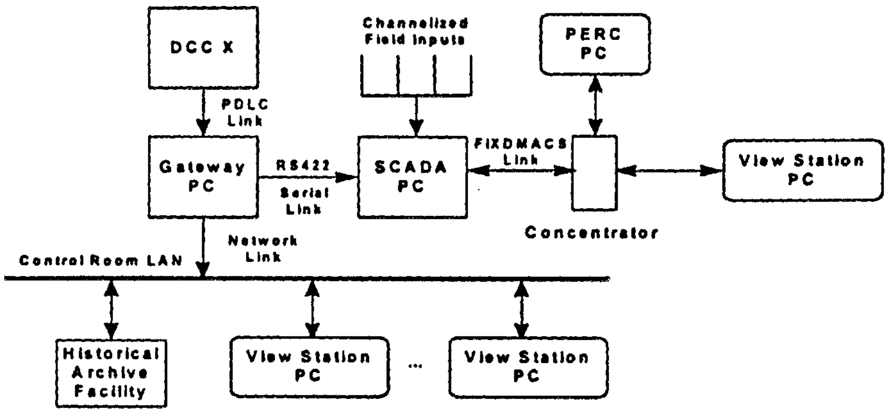

Figure 1. Pickering 'B' NGS Data Extraction System

The Point Lepreau GS (New Brunswick Power) HDS implementation is referred to as the Gateway Computer System (GCS) [2]. The system collects data from a number of sources, including the DCC's, the Safety System Monitoring Computers (SSMC), and D_2O Vapour Recovery System (DVRS). Data is stored in time-stamped (from 100 ms to 6 s resolution) flat files and data extraction can be performed from any desktop computer connected to the site LAN using in-house developed applications such as the System Engineer's Data Extractor (SEDE) and Monitoring System (SEMS). SEMS is used to monitor live or near-real time data that is broadcast every 6 s and SEDE is used to extract historical data to a standard file format that can be viewed with any off-the-shelf spreadsheet or data visualization package.

The Gentilly-2 NGS (Hydro Quebec) HDS implementation, known as the Système de Traitement des Données d'Exploitation (STDE), translates to English as "an operation (or plant) data processing system". The objective of STDE was to provide system engineers with access to life-of-plant process data from their desktop PCs [3]. The architecture of STDE (see Figure 2) contains three levels of file servers, to protect against loss of data. Gateway computers (LCX and LCY) receive data from the DCC's and transmit it every five seconds to the first level file server (LCSD1). The LCSD1 server sends data files to the main file server (TDESD2) using network file services. The LCSD1 server has the capacity to buffer data for up to three days should the LAN or main file server fail. The LCSD1 server is also designed to feed data to future real-time applications in the control room. The main file server (TDESD2) stores more than 100 days of historical data including alarm, incident-related, and test data on disk and archives the data in a carousel of magnetic tapes (250 Gbyte capacity). End-user PC desktops are supported by client applications that run remotely on a host UNIX computer (TDEST), which is connected to the main file server through an FDDI ring and fire-wall. The fire-wall provides data security by allowing only authorized users to access the data. The predominant desktop environment is MS-Windows and end-user applications run in the X-Windows display environment. Functions of the end-user application tool suite include data extraction and logging, trending, event search capability, and support of alarm page extraction.

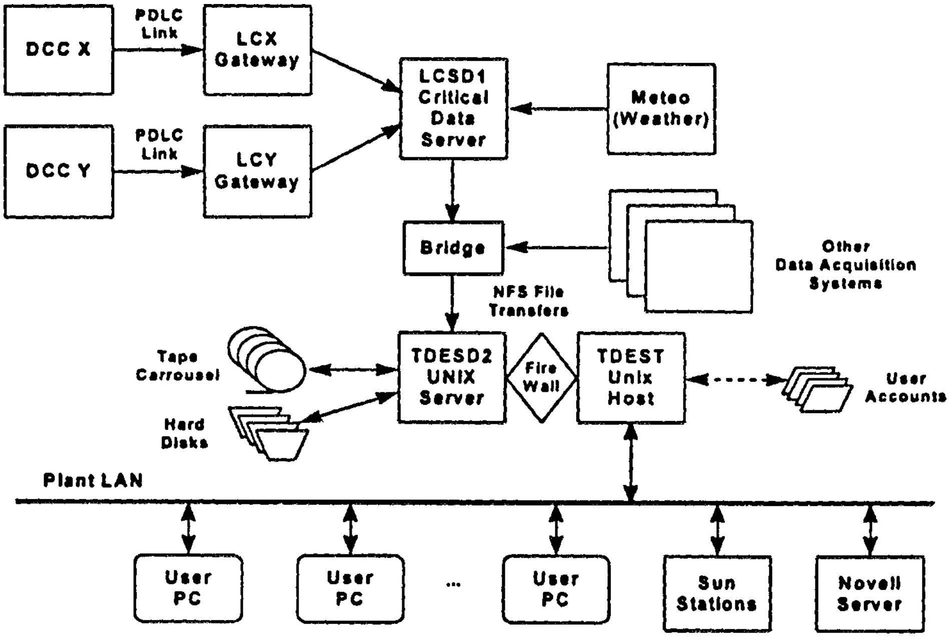

Figure 2. Gentilly-2 STDE System

3. LIMITATIONS WITHIN CURRENT HDS IMPLEMENTATIONS

As outlined in the preceding section, there is wide diversity in HDS design and implementation strategy in Canadian CANDU stations. Although not applicable to all systems, current limitations include:

- insufficient historical data collection and storage from all data sources including the DCC's,
- limited historical data storage and retrieval capability for both short-term and life-of-plant data,
- HDS server and LAN architectures that limit transmission flow and create data bottlenecks,
- limited user accessibility to the HDS across the entire plant,
- the lack of user-friendly end-user tools for data extraction, visualization, and analysis that allow customization and a full range of functionality without requiring computer programming skills,
- insufficient integration of HDS information with data from work management and other business systems,
- limited tools and utilities to support data and system configuration, management, and administration,
- the lack of data validation and security services, and
- the need for large and costly support teams to manage and continuously improve the systems and to customize user interfaces.

These limitations and issues ultimately decrease the effective use and benefits of a plant-wide HDS and must be addressed within the framework of short-term and long-term strategies for plant information system technologies and the implementation of common HDS environments across the Canadian nuclear industry.

4. A MODEL FOR PLANT-WIDE HISTORICAL DATA SYSTEMS

The vision for future plant-wide historical data systems is an architecture that is flexible, expandable, open, reliable and supportable, in order to allow for the integration of next-generation systems and technologies into the HDS. The plant HDS must be able to support many remote users and interface to multiple plant data systems. Data management facilities must exist to maintain and coordinate the large amount of data within the HDS and the design must allow for component failure or shutdown due to maintenance with minimum impact on the data collection and overall system performance.

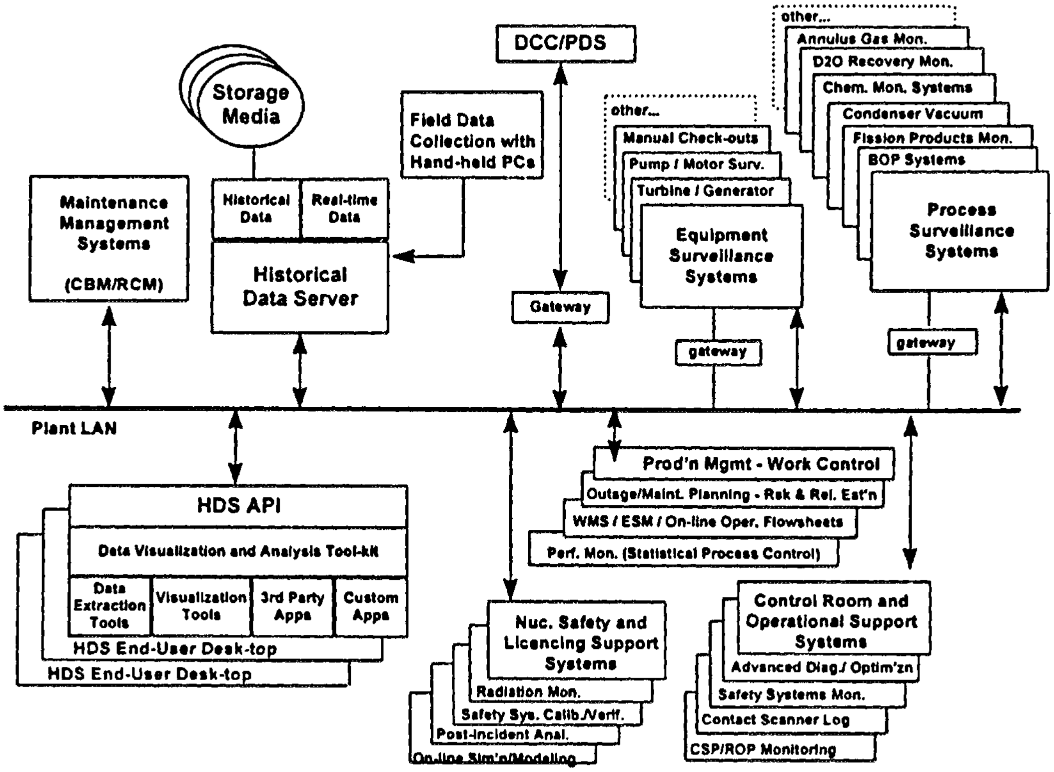

Figure 3. Integrated Historical Data System Architecture

Figure 3 shows a block diagram of the generic HDS architecture within the context of an overall information technology plant data system capable of supporting long-term plant requirements. The desired HDS architecture is a client-server design capable of supporting many remote end-users with interfaces to multiple plant data sources and information systems, all supported on-line over the station LAN. The HDS must provide interfaces to a large number of plant safety, control, and special data acquisition systems. Gateways and fire-walls are required for data buffering and for protecting the functionality, performance, and integrity of the control and safety systems from which data is being acquired. Interfaces are also required to support HDS maintenance and system management. Individual users from all plant functional disciplines require tool-kits for HDS data access, data visualization and analysis, reporting, and archival activities required for each of their job functions. This includes interfaces for system responsible engineers (nuclear and balance-of-plant systems), program responsible engineers (physics, chemistry, thermodynamics, safety, licensing, etc.), maintenance and production staff, and management. HDS interfaces to portable hand-held computers and data acquisition systems are also necessary in order to support the acquisition and storage of data from field instruments and devices not connected to the station LAN [4]. Multiple on-line HDS data servers may be required to achieve the desired performance, capacity, and maintainability. Additionally, the HDS must provide horizontal integration of its data with other plant databases and information systems including work management systems, maintenance management systems (including CBM and RCM components), material management systems, and others. To achieve and maintain this vision, the HDS must be based on open architectures, industry standards, and the integration of commercial off-the-shelf products and components that will minimize the effects of hardware and software obsolescence. Generic HDS functional requirements have been developed to support the ongoing development and implementation of historical data systems within the Canadian CANDU environment. These requirements are outlined below.

A large number of HDS data sources are envisaged since the HDS is intended to be the repository of all historical plant process data, independent of its point of origin. These systems include DCC's, the Plant Display System (PDS), SSMC's, process controllers, special data acquisition systems, chemistry monitoring systems, manually collected data via hard-copy and hand-held computers, and others. The HDS is not intended to be used as a data repository for engineering, work management, material management, and financial information systems. However, the HDS user tool-kit must be capable of accessing and using the data from these other systems in order to provide users with a truly integrated environment.

A wide range of data types must be supported to provide an accurate picture of current and past plant operations. The correlation of events (e.g., alarms and equipment operational status changes) with process data (e.g., flows and pressures) is required in order to provide detailed analysis and diagnosis of plant operation. Test data and results from analysis and modeling tools must also be stored by the system and be accessible on-line for the verification of results. The HDS must be capable of handling analog and digital data, calculated values, end-user calculated values, alarm and event logs, and test logs. Future considerations may also include the use of digital video signals and related technologies.

Plant data must be collected and stored as a function of its fundamental accuracy and time resolution. Several years of on-line data must be accessible to provide the ability to pick up seasonal variations and perform long-term monitoring functions. Historical data permits the user, with the appropriate software tools, to estimate the condition of equipment and components, to explain operational trends and deviations, and to predict and ultimately avoid failures. Data storage requirements include:

- the scanning and storage of a minimum of 20 000 tags per CANDU unit,
- configurable scan rates ranging from milliseconds to days, with change of value, event triggered, and burst mode capabilities,
- the capability to store high frequency data from special data acquisition systems,
- a minimum of five years of on-line data,
- life-of-plant data available as either on-line data or archived in accessible off-line storage, and
- configuration tools to facilitate revisions to database information such as tag descriptions, units, alarm types, sample frequency, etc.

In order to take advantage of the plant-wide HDS, data retrieval must be simple, user-configurable, and retrieval response times must be in the order of seconds. Many users will also require access to near real-time data for monitoring and analysis. Data retrieval requirements include:

- user access to on-line and off-line data using well-defined data retrieval functions,
- data access and retrieval using industry standard interfaces such as structured query languages,
- data retrieval functions for browsing system information and the selection of data from tag lists, tag descriptions, and alarm lists from both on-line and off-line data,
- the ability for users to save their own data retrieval configurations,
- warning messages to notify users of data access or retrieval errors, and
- retrieval functions capable of handling different sample frequencies, time gaps, overlaps, and time synchronization problems between the various data sources and interfaces.

The plant-wide HDS also requires a wide range of data analysis and visualization tools to support the varied and specialized tasks performed by users. These tools can be integral to the plant-wide HDS or may be part of a separate stand-alone tool-kit. The requirements for data analysis and visualization tools include:

- user-friendly graphical user interfaces with HDS application programming interfaces (API) to support user access and retrieval of HDS data from all previously defined data sources,
- capability to select from pre-configured displays and trends,
- capability for users to easily configure and save custom displays and trends,
- data interpretation and display functions including multiple window displays of historical trends (graphic and numeric), charts, lists, 2-D and 3-D graphics, and data editing,
- data analysis functions including data editing and filtering, standard and complex mathematical analysis, curve fits, statistical analysis, limit and spread checking,
- real-time and near real-time monitoring functions including trends, animated graphics, virtual instruments, process schematics, bar-charts, boundary checks, and the triggering of other actions and processes based on current plant events, and
- user-configurable reporting and data storage including plotting capabilities, importing and exporting of data and object linking data elements (graphs, plots, charts, etc.) to word processors, spreadsheets, and other standard office software for automatic report generation.

Data validation is required to ensure the accuracy of data that is relied upon by station personnel in order to make decisions for maintenance, performance enhancement, troubleshooting, problem avoidance, and other tasks. Data validation requirements include:

- data gathering interfaces that monitor data transfers and log errors,
- consistency checks of related data streams, and
- validity checks from any on-line instrumentation.

Data security is required to maintain the integrity of the plant data. It is necessary to eliminate the possibility of unauthorized system access or data corruption. Specific data security requirements include:

- data protection to ensure that HDS data cannot be modified by users or system maintainers,
- security features to prevent unauthorized access to all or selected data contained in the system,
- utilities to allow security permissions and user accounts to be setup and modified,
- security measures to control data entry such as user-derived points or manually-entered data, and
- utilities and procedures for data management and backups.

The requirements of configuration management are to identify the system configuration at discrete points in time, as well as to control and verify all configuration changes. These requirements include:

- procedures and utilities to ensure that configuration changes are made in accordance with approved verification and validation standards, site policies, and procedures,
- tools to define and modify the standard configuration for users from a central point,
- the ability to deliver or update versions of software to users from a central point, and
- provisions to maintain a common database for storing system management and configuration details.

HDS data communications design must allow for the movement of large amounts of data between networked computer systems while minimizing communication bottlenecks. Communication requirements include:

- the use of industry standard communication protocols such as TCP/IP,
- the use of industry standard hardware that supports high speed data transfer to LAN systems, and
- the ability to implement future upgrades to the hardware and software as LAN systems evolve to support higher bandwidths, video data, and new technologies such as asynchronous transfer mode communications.

5. HDS MANAGEMENT AND IMPLEMENTATION ISSUES

As each plant HDS has become more widely used and integrated to a host of other systems, a number of issues have surfaced with respect to work practices, data ownership and management, security, reliability, data validation, and restrictions on access and use of the data based on software classification and quality levels.

The introduction and evolution of HDS environments in the stations is resulting in two fundamental developments affecting day-to-day operations, decision-making, and work flow: data traditionally available only to the operators is becoming available to engineering, maintenance, and nuclear safety staff; and data traditionally not available in the control room is being made available to operators. These developments, in conjunction with the introduction of enhanced surveillance and maintenance programs, will significantly impact roles, responsibilities, and work procedures.

One of the more complex challenges to the successful development and implementation of an integrated plant-wide HDS will be the overall strategy, governing policies, procedures, and mechanisms for data ownership, maintenance, and management. As the HDS grows and interfaces with a greater number of plant-wide data providers and users, the issues associated with data management increase in importance. It is conceivable that, in the future, the HDS will be expected to handle anywhere from 1-5 Gbytes of new data daily. Two strategies for handling this issue have been raised. One strategy is to implement tight configuration control over what data is archived, in what form, and how often. The alternative to this is to provide tools to the end-user, who in turn would take responsibility for configuring and defining data formats and storage strategies. A likely scenario as the HDS evolves, will be that both approaches will be used together in balance. Critical process data will be under tight centralized configuration management, while end-users and system responsible engineers will have sufficient tools and system resources to allow them to configure their systems to their specific local needs.

System security to ensure data integrity and to prevent unauthorized access must also be addressed. One approach is the use of network fire-walls (as implemented within the Gentilly-2 STDE system), whereby an agent process acts on behalf of the end-user client process, and interacts with the historical data-base archive server for the purpose of data extraction. This approach eliminates the possibility of unauthorized system access, data extraction, or file corruption. Using this approach provides a high degree of confidence that once the data is captured by the system and validated through consistency checks and/or even manual inspection (where practical), its integrity is maintained over time. Similar strategies could be implemented if the HDS were developed as a plant-wide "client-server" system.

System reliability becomes an increasingly important issue as the station HDS is relied upon in supporting many of the day-to-day functions of engineering services and operations staff. One of the key success factors in achieving this goal is to ensure that the design implements an architecture and functionality that will meet system reliability and performance requirements. Simple strategies such as hardware redundancy, back-ups, software error and exception handling, and system diagnostics may increase the up-front development cost, but quickly justify themselves once the system is in service.

Data validation is another increasingly important concern and is an issue both inside and outside of the control room. Current Canadian CANDU practice limits HDS use in the control room to display-only systems with the onus on the operators to validate the data against qualified panel instruments and displays. Similarly, data validation is also an issue as data is relied upon outside of the control room for surveillance, maintenance, safety and licensing analysis. Currently, the onus is on the user to perform validation and consistency checks before making any decision based on HDS data. This is done by comparing data on the desktop to data acquired in the field, and checking that measurement instruments are within calibration tolerances. As HDS use becomes more wide-spread, data validation issues must be addressed in terms of software classification and qualification as discussed below.

Software classification and quality assurance is a key issue in the implementation of a plant-wide HDS, particularly as HDS data is requested for use by control room operators, safety, and licensing functions. The software classification and future development of an HDS in Canadian CANDU stations should be based upon the Ontario Hydro - AECL Software Engineering Standards (OASES) [5]. The OASES categorization of software and software-controlled systems in nuclear applications is based on the failure impact the software may have on the ability of the larger system in which it is a part, to perform any of its necessary safety functions. Within this framework, software failures are classified as Type I, II, or III (Type 1 failure being the most severe), and software quality category levels are defined as Levels 1 through 4 (Level 1 being the most rigorous). Clearly, the software failure type and software quality levels are linked to the end-use of the HDS data. HDS failures classified as Type III with software quality levels categorized as Level 4 are appropriate when the data use is not safety-related or when data can be validated from other qualified sources. The failure classification and software categorization levels will require reassessment when used outside of this context. Additional emphasis would be have to be put on system reliability, data integrity and validation. Qualification of pre-developed software used in the HDS software development life cycle would also have to be considered.

6. OPPORTUNITIES FOR PLANT-WIDE DATA SYSTEMS INTEGRATION

A wide variety of applications have been identified as benefiting from the better use of plant data through the implementation of plant-wide historical data systems. These have been grouped into the following categories:

- Engineering Services and Technical Surveillance Systems,
- Control Room and Operational Systems,
- Production Management and Work Control Systems, and
- Safety and Licensing Support Systems.

Although each station is slightly different, Canadian CANDU station engineering service groups are generally known as technical units. System engineers and specialist engineering groups interact daily with operators, production, and maintenance staff. Their job functions include technical surveillance, troubleshooting, production support, maintenance support, project support, and operations support. Their goals are to increase plant performance (capacity factors), availability, and safety. The technical units have a fundamental need for accessible plant data for analysis in support of their job functions. The implementation of a plant-wide HDS will have a significant impact in optimizing technical surveillance programs in support of:

- system and plant performance improvements,
- maintaining, modifying, and managing the plant configuration,
- regulatory compliance and environmental monitoring,
- troubleshooting, post-incident investigation and analysis, and
- maintenance support, including CBM and RCM programs, implementing a wide range of system and component monitoring in the areas of pumps, valves, turbines, electrical equipment and motors, plant chemistry, and others.

Historical data is also of value in control room and operational systems. With a properly qualified HDS, or other methods of data verification and validation, historical data can be use for:

- critical safety parameter monitoring,
- heat balance monitoring,
- flux mapping and fuel handling,
- shutdown system monitoring,
- operator day logs and alarm recorders,
- advanced decision support systems including real-time simulation and analysis, and
- plant display systems.

Production management and work control can also benefit from the integration of HDS data with plant work management systems contributing to:

- outage and maintenance planning,
- CBM and RCM programs,
- plant configuration management and the tracking and verification of operating orders,
- on-line operational flow sheets, and
- risk and reliability analysis of plant systems and components.

Plant-wide HDS information is also crucial to a variety of safety and licensing support programs such as:

- radiation monitoring including post-accident analysis, radiation dose information, and dose management,

- regulatory compliance monitoring to verify component and system performance are within safety margins,
- testing, parameter verification, and calibration of safety-related systems and components, and
- on-line analysis and simulation models for primary heat transport circuit analysis, heat balance, and simulation of reactor operations.

7. SUMMARY

It is clear that plant-wide historical data systems including data extraction, interpretation, analysis and reporting tools are steadily increasing in importance across virtually all areas of plant operations. The implementation of HDS technology is critical to the execution of technical surveillance and analysis programs, operational analysis, production and maintenance, and safety and licensing programs. The current introduction of plant information systems is having a major impact on the daily operations of the plant at all levels. Although there has been significant progress, there is also a great diversity amongst Canadian CANDU plants in HDS design and implementation philosophy. Consistent industry-wide HDS information technology strategies are required to reduce potential duplication of effort and minimize HDS design, implementation, and support costs.

The requirements for HDS technology to support all aspects of nuclear plant operations and maintenance are becoming much better understood as the use of HDS technology evolves within the plant environments and industry studies are conducted to derive generic requirements and specifications. The introduction of new technologies and the advancement of off-the-shelf HDS products including database systems, data visualization, and analysis tools is now permitting the introduction of historical data systems with significantly less development effort. Similarly, world-wide competitiveness and the recognition of the value of integrated data systems have also led to the development of off-the-shelf HDS products with built-in data links to CBM programs and large integrated work management systems.

The industry must continue to strive for reduced OM&A costs while at the same time increasing plant performance and safety. The use of HDS technology providing easy data access, visualization and analysis capability to all plant staff will directly contribute to these goals.

8. ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of the Canadian CANDU utility and design organization partners participating in the review of current HDS implementations, the development of generic HDS requirements, and the development of PC-based tools for technical surveillance and analysis. In particular, the authors would like all of the staff who provided assistance from Ontario Hydro (Bruce NGS, Pickering NGS, and Darlington NGS), Hydro Quebec (Gentilly-2 NGS) and New Brunswick Power (Point Lepreau GS).

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PROCESS VARIABLES CONSISTENCY AT ATUCHA I NPP

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ABSTRACT

A method to evaluate the different systems performance has been developed and is still under assessment. In order to perform this job a process computer upgraded in 1992 was used.
In this sense and taking into account that the resolution and stability of instrumentation is higher than its accuracy process data were corrected by software.
In this way, much time spent in recalibration, and also human errors were avoided. Besides, this method allowed a better record of instrumentation performance and also an early detection of instruments failure.
On the other hand, the process modelization, mainly heat and material balances has also been used to check that sensors, transducers, analog to digital converters and computer software are working properly.
Some of these process equations have been introduced into the computer codes, so in some cases, it is possible to have an "on line" analysis of process variables and process instrumentation behaviour.
Examples of process analysis are:
-Heat exchangers, i.e. the power calculated using shell side temperatures is compared with the tube side values.
-Turbine performance is compared with condenser water temperature.
-Power measured on the secondary side (one minute average measurements optimized in order to eliminate process noise are compared with power obtained from primary side data)
-The calibration of temperatures have been made by direct measurement of redundant sensors and have shown to be the best method.
-In the case of pressure and differencial pressure transducers are cross checked in service when it is possible.
In the present paper, details of the examples mentioned above and another ones are given and discussed.

1. INTRODUCTION

Atucha I NPS is a 360 gross Mwe heavy water cooled and heavy water moderated reactor. It has been operating since 1974 with a load factor of 69.5% and an availability factor of 75%. A brief description of this station can be read in another paper presented at this meeting [1].
Instrumentation and control technology belongs to earlies 70's. The control system is analogic. There was also a computer installed but only for data adquisititon and a few on line calculation.
In 1992 data from computer was sent to a PC's system with a special software developed by the Computer Division of Engineering Department of the Station and the Centro Atómico Bariloche, one of the reseaich centres of the Comisión Nacional de Energía Atómica.
Also a software facility that allowed the operator to access to present an historical values of plant variables was developed.
This paper is about using the data to check that instrumentation is working properly and to perform some calculations that permits process data analysis.
The analog digital converters A/D C's, included in the computer measure voltage through 20Ω resistors in 0-20 mA current loops connected to the transducers either directly or by mean of galvanic separators in those cases in which that signal could produce a reactor trip.

2. THERMAL MEASUREMENTS

It is very well known that resolution and stability are higher than accuracy. The initial method to verify the accuracy of thermometric measurements was as follows: during hot shut-down, pressure in the steam generators was kept constant, obtaining in this way constant temperature in the totality of the sensors. Actual temperature was obtained using steam tables and correlations for temperatures differences between primary and secondary

side when steam generators are dissipating only the power produced by primary coolant pumps and no more than 2 Mw of decay heat. The temperature measurement errors were tabulated and used when necessary to perform different calculations.
This method was changed in 1995 by the method of direct reading of the spares RTD and thermocouples, while mantaining constant temperature in the whole reactor.
The condition for a spare RTD to be taken as a reference is that when the thermoelement terminals are short-circuited the resistance between any pair of the three wires (RTD's tranducers in this station measures by means of three wires), showed differences not higher than .03 Ω.
When in hot shut down condition the cross check calibration described by H. Hashemian [2] is used to determine the proper working of the thermoelements. In table 1 is it posible to observe an example of this measurements.

3. PRESSURE TRANSDUCERS.

In some cases during shut-downs it is possible to make the cross-check between different pressure instruments.

4. DIFFERENTIAL PRESSURE TRANSDUCERS.

When it is possible to set some plant valves in such a way that the flow through two flowmeters is the same the cross check between flowmeters can be perfomed.

5. CURRENT STATE OF PROCESS DATA ADQUISITION AND ANALISIS SYSTEM AT THE STATION

This paper will be addressed now to the job done either to perform the surveillance of different processes or the proper operation of the instrumentation.
Current state of process data adquisition system at the station:
Figure 1 shows schematically the system for data adquisition and data processing. Dashed lines enclosed the remaining parts of the initial computer.
Software correction on process variables are performed in Computers A and B. Variables that represent the same physical parameter should in this case indicate the same value and a difference may indicate a malfunction either of a sensor or a transducer.
Process analysis codes are also resident in the same computers .
All values generated in computer A and or B are sent to the user computers.
Besides in order to perform the cross calibration of A/D C'S a current loop with the same current (about 10 mA) that introduces the same signal in the four A/D C's was installed.

6. SOME EXAMPLES

6.1 Reactor thermal Power Measurement

Reactor thermal power measurements are based on feed-water and blowdown flow rate. The enthalpy and mass balance in the reactor is performed. Main Pumps power and inventory control system losses are taken into account. Since water flow measurements are noisy calculations are made over a 1 minute measurement average.
Consistency test is perfomed by the quotient between power calculated in each steam generator secondary side and the enthalpy difference in primary side, to obtain this value the difference of temperatures measured across the steam generator and the reactor inlet temperature are used in order to improve accuracy. The value obtained is the mass flow-rate across steam generator primary side and it is almost a constant since the pump flow changes very little for a given power (it depends in this case only on fluid density and net frequency). Also the zero steam quality at reactor outlet is important in this calculation.

6.2 Turbine Performance

At a given power, turbine performance is only a function of steam pressure, feed water temperature and river water temperature. Vacuum in the condenser is also function of this two variables. This measurement also constitute a test of consistency.

6.3 Power transmited at moderator heat exchanger.

If measurements are accurate enough, power measured from secondary side data should be equal to the value of primary side within an error of 1.5 Mw. (Power in moderator coolers for 100 % Power ranges between 100 and 110 Mw depending on plant condition).

6.4 Steam Generators and Moderator Coolers Heat Transfer Coefficient

Heat transfer coefficients for SG's and Moderator Coolers are also calculated .Analysis of this data allowed us to understand the behaviour of one of the moderator heat exchanger analized in a paper presented at this meeting [1].

7. CONCLUSIONS

Process variables consistency analysis constitutes a powerful tool to make early diagnosis of processes or instrumentation performance. It also may have an important impact on the plant economy since it permits an increase of the accuracy of the power measurement and also in plant safety and reliability, because safety related instrumentation may be cross checked with the validated process instrumentation.

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NUREG/CR-5560

Table I

Signal	Resistance
	Ω
QM01T022	182.0
QM02T022	181.98
QM00T021	182.11
QH01T006(GE30)	182.12
QH02T006(GE30)	182.15
QH02T007	182.51
QH01T007	182.04
QH02T008	182.13
QH02T006	182.10

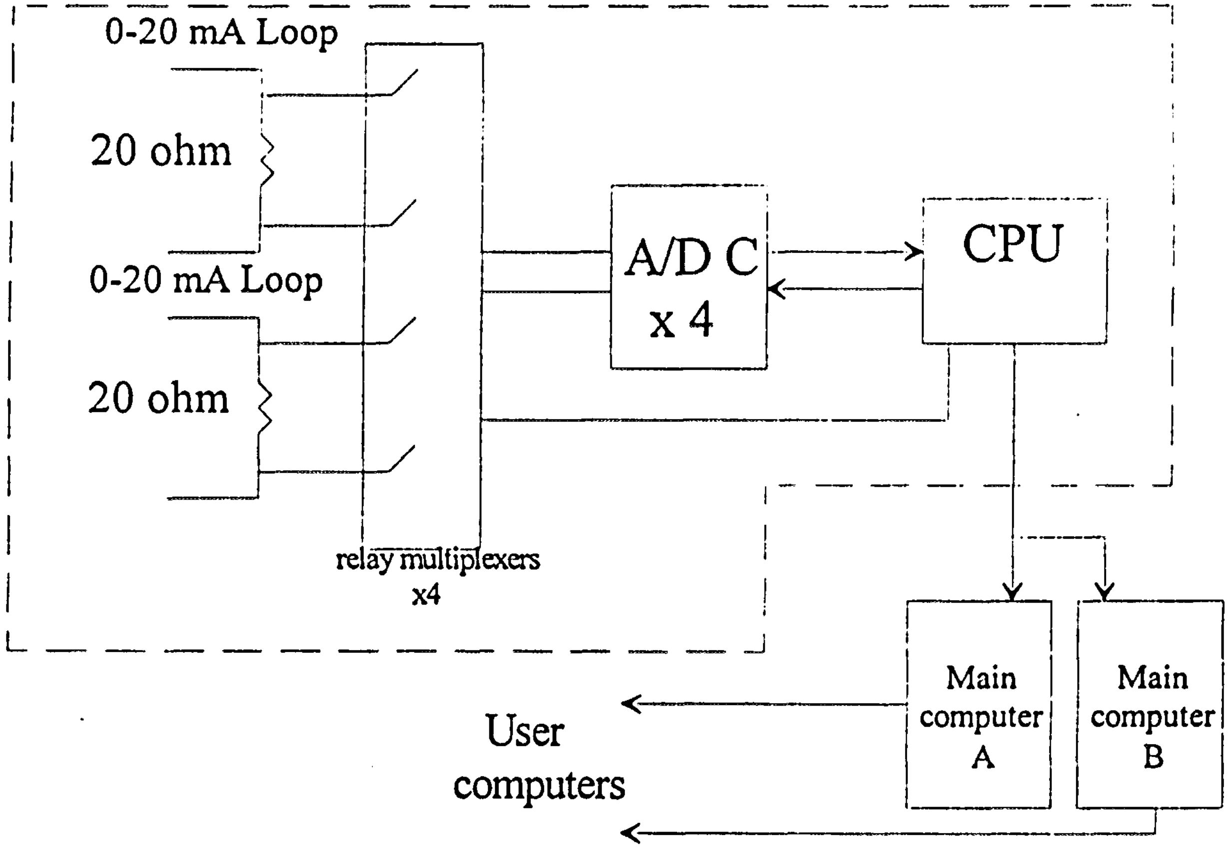
0-20 mA Loop
20 ohm
0-20 mA Loop
20 ohm
relay multiplexers
x4
A/D C
x 4
CPU
Main
computer
A
Main
computer
B
User
computers

Figure 1.

Session 4
Advanced Techniques

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SESSION 4

ADVANCED TECHNIQUES

Chairpersons: Ms. J. Baldwin, U.K.
Mr. G.B. Moutry, U.K.

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INSTRUMENT SURVEILLANCE AND CALIBRATION VERIFICATION THROUGH PLANT WIDE MONITORING USING AUTOASSOCIATIVE NEURAL NETWORKS

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Abstract

The approach to instrument surveillance and calibration verification (ISCV) through plant wide monitoring proposed in this paper is an autoassociative neural network (AANN) which will utilize digitized data presently available in the Safety Parameter Display computer system from Florida Power Corporations Crystal River #3 nuclear power plant. An autoassociative neural network is one in which the outputs are trained to emulate the inputs over an appropriate dynamic range. The relationships between the different variables are embedded in the weights by the training process. As a result, the output can be a correct version of an input pattern that has been distorted by noise, missing data, or non-linearities. Plant variables that have some degree of coherence with each other constitute the inputs to the network. Once the network has been trained with normal operational data it has been shown to successfully monitor the selected plant variables to detect sensor drift or failure by simply comparing the network inputs with the outputs. The AANN method of monitoring many variables not only indicates that there is a sensor failure, it clearly indicates the signal channel in which the signal error has occurred.

1. INTRODUCTION

Traditional approaches to instrument calibration at nuclear power plants are expensive both in labor and money. These approaches vary from calibration by replacement, to transfer calibration using standard instruments. Technical Specifications require specific instruments be calibrated on time tables that coincide with the original fuel cycle of the plant. These calibrations require that the instrument be taken out of service and be falsely-loaded to simulate actual in-service stimuli. This can lead to damaged equipment and incorrect calibrations due to adjustments made under non-service conditions. While proper adjustment is vital to maintaining proper plant operation, a less invasive technique is desirable.

As utilities move to 24 month fuel cycles, there is a needfor performance based calibration requirements. When implementing performance based calibrations, the instruments are calibrated only when necessary. Monitoring instruments for calibration performance will allow nuclear utilities to reduce the efforts necessary to assure the instruments are calibrated. Benefits include an industry wide cost savings, less time for reactor startup, and easier compliance with NRC Generic Letter 91-04 for extending calibration intervals.

The use of AANNs for plant wide monitoring was developed by the University of Tennessee and reported in NUCLEAR TECHNOLOGY.[1] This work, using data from the Experimental Breeder Reactor II, has demonstrated the practicality of this application. Related work includes monitoring of the Borssele Nuclear Power Plant using AANN techniques.[2] Similar work using AANN applied to chemical process systems have also been reported.[3,4,5] This work further advances the methodology by introducing a robust training method and use of the sequential probability ratio test (SPRT) as a sensor failure detection device.

An autoassociative neural network (AANN) is one in which the outputs are trained to emulate the inputs over an appropriate dynamic range. Many plant variables that have some degree of coherence with each other constitute the inputs. During training to make each output equal to the corresponding input, the interrelationship between the variables is embedded in the connection weights. As a result, any specific output shows virtually no change when the corresponding input pattern has been distorted by noise, missing data, or non-linearity's. This characteristic allows the AANN to detect drift or failure by comparing the sensor output with the corresponding network estimate.

2. PARAMETER SELECTION

Previous studies indicate that the degree of correlation between the input variables is relatively significant for an autoassociative neural network to function as a complex system monitoring device.[1 3] Under these circumstances, changes in one input variable due to drift, channel deterioration, or failure will not significantly change the corresponding value of the output because the output is related to all the other correlated input variables through a large number of paths and weights.

Parameters were selected based on plant safety points that require close monitoring (labeled Tech spec.), and the degree of coherence between the parameters statistically determined using linear correlation coefficients given by:

$$S(i,j) = \frac{C(i,j)}{\sqrt{C(i,i)C(j,j)}}$$

where C is the covariance matrix.

The coefficients range from ± 1 with the highly correlated parameters at the boundaries of the range. A value near ± 1 means there is a direct relationship between the change of a parameter with respect to another. If two signals showed no change with time (flat), there correlation would be near zero. The average coefficient value for the network was 0.28. Table 1 shows the 22 plant parameters selected for this study.

This grouping primarily consist of primary side parameters such as flows, pressures, and temperatures. The network includes 14 parameters listed as "Tech spec" safety parameters that must be monitored closely.

3. NETWORK ARCHITECTURE

The network architecture selected is a three hidden layer feedforward AANN proposed by Kramer[4]. It consist of an input layer, 3 hidden layers, and an output layer. The architecture is shown in Figure 1. The first of the hidden layers is the *mapping layer* with dimension greater than the number of input/outputs. The second hidden later is called the *bottleneck layer*. The dimension of this layer is required to be the smallest in the network. The third hidden layer is called the *demapping* layer that has the same dimension as the mapping layer. Kramer points out that five layers are necessary for such nets in order to model non-linear processes.

The three hidden layers form a "feature detection" architecture in which the bottleneck layer plays the key role in the identity mapping. The mapping layer maps from the input data space to the non-linear principle component score space (bottleneck layer), and the demapping layer map from the non-linear principle component score space to the data space (network output) corrected by the non-linear principle components.

The bottleneck layer prevents a simple one-to-one mapping from developing during network training. If the network learned the identity function exactly, it would be of little value. The bottleneck layer provides an internal constraint that prevents the net from strictly learning the identity mapping. Essentially the bottleneck layer functions like a non-linear principle component analysis (NLPCA) filter that gives a richer representation of the data: using a lower dimension to explain maximum information. The outputs of the bottleneck layer are non-linear principal components, which have a clear interpretation in theory.

The mapping-bottleneck-demapping combination forces the network to develop a compact representation of the

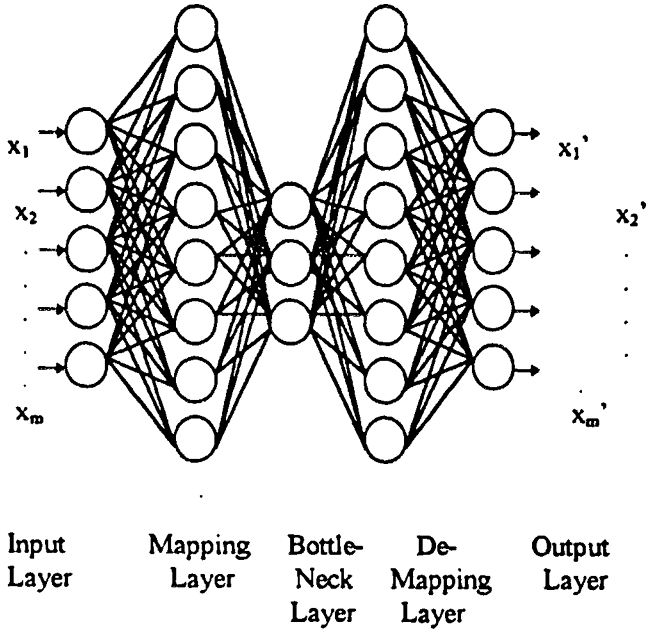

Figure 1. Architecture of the AANN

training data that better models the underlying system parameters.

The non-linear transfer function of the three hidden layers are sigmoidal logistic functions given by:

$$\sigma(x) = \frac{1}{1+e^{-x}}$$

The network uses a linear output layer which allows for a mathematical regression technique (SVD) to solve for the output weights.

3.1. Selection of Hidden Layer Nodes

In the combined network, let m be the number of nodes in the input and output layers, f the number of nodes in the bottleneck layer, and M the number of nodes in the mapping and de-mapping layers. The number of input and output nodes (m) depends on the number of input/output parameters in the network. However, there is no definitive method of deciding a priori the number of nodes in the mapping and de-mapping layers (since the number of mapping nodes is equal to the number of de-mapping nodes, from this point on they will be referred to as mapping nodes). Generally, the number of mapping layer nodes is related to the complexity of the non-linear parameters that can be modeled by the network. To few nodes and the accuracy could be low due to the limited representational capacity (to few degrees of freedom) of the network. If there are to many nodes, the network is prone to overfitting, or learning the stochastic variations in the data rather than the underlying functions. A simple approach for determining the number of mapping layer nodes is restrict the number of weights in the network to a fraction of the number of constraints imposed by the network. For the combined architecture, assuming all nodes have biases, the number of adjustable parameters in the network is given by the inequality[4]:

$$2M << m(n - f)/(m + f + 1)$$

where n is the number of training patterns. Kramer gives two other methods that may be used to determine the optimum number of mapping layer nodes; the Final Prediction Error (FPE), and Akaike's Information theoretic Criterion (AIC).

Recall that the bottleneck layer of the network functions as a Non-Linear Principle Component Analysis filter (NLPCA). The bottleneck layer requires as many nodes as there are non-linear factors in the parameters that are modeled. Therefore, the number of bottleneck nodes can be determined using an algorithm that statistically determines the principle components in a data set.

The non-linear approach is the same as the linear approach except that the data is summarized with a smooth curve (instead of a straight line) which is determined by non-linear relationships among all the variables. Given a data set X which contains n samples of m parameters can be expressed in terms of l non-linear principal components (number of f non-linear bottleneck nodes) as:

$$X = F(T) + E$$

where T is defined as the non-linear principal component scores, and F is defined as the non-linear principle component loading functions[5]. An example of such an algorithm to determine the non-linear principle components can be found in Hastie and Stuetzle[6].

Due to repeated training and testing trials, empirical formulas have been arrived at to determine the optimal number of hidden nodes in each of the hidden layers. They are given as ratios of one layer to another (for example input to bottleneck) and are listed below. Theses are only in approximate ratios based on the parameter groupings used this project.

$$M/m \cong 1.25 \qquad M/f \cong 1.6 \qquad m/f \cong 1.3$$

These were used in conjunction with Kramer's inequality equation given above to determine the number of hidden layer nodes for each of the networks.

The dimensions of the network presented here are (22-27-18-27-22), the number of inputs, mapping, bottleneck, demapping, and output nodes respectively.

4. NETWORK TRAINING

The network was trained using MATLAB'S[7] fast backpropagation trai:ing algorithm which incorporates an adaptive learning rate and momentum. Input and target vector were linearly scaled between 0.1 and 0.9 to simplify training. 425 representative training patterns were selected from a possible 3344 patterns recorded every 15 minutes (5 weeks of operation) during full power plant operation. Two transients occurred during the full power operation and were trained into the network.

Since a linear output layer was used, training was greatly accelerated by solving for the output layer weights using a singular valued decomposition mathematical technique (SVD) instead of iterative training. By using the SVD method to approximate the optimal weights, not only do we reduce training time but the weights are vastly superior to what would be attained by random iterative methods. The provide an excellent starting point for iterative methods applied to all weights later in the backpropagation algorithm. A robust training technique will also be discussed which vastly improves the fault detection capabilities of the network.

4.1. Network training (stopping) criteria

It was found early on in this study that the training error goal of the network is a very important consideration for a robust network that can generalize well. Real plant operational data contains a small amount of noise (typically 2 to 3 percent) from the sensors and other electronic equipment. If a network is trained to a low error value, it will tend to model the noise in the data and not the overall functions behind the data. Typically this is known as overfitting the training set. This creates a network that has very poor generalization ability and practically no use for its intended purpose. Two methods are used to prevent overtraining the network. The first method is to statistically determine the amount of noise in the signals and calculate an overall training error goal from the noise estimates. The second technique used is cross validation training[8] to verify the results of the first method.

4.2. Singular Valued Decomposition (SVD)

Since a linear output layer was used, training was greatly accelerated by solving for the output layer weights using a singular valued decomposition mathematical technique (SVD) instead of iterative training[8]. By using the SVD method to approximate the optimal weights, not only is training time reduced, but the weights are vastly superior to what would be attained by random iterative methods. They provide an excellent starting point for iterative methods applied to weights in the hidden layers optimized using a backpropagation algorithm.

In this method only the most relevant information is retained to compute the weights, or it's principle component vectors. The least important information is discarded because it is most likely nothing more than noise.

4.3. Robust Network Training

A robust network is one that will estimate the correct output for a respective input that contains an error or missing data, without disturbing the output estimates of the other parameters in the network. Robustness to errors is not automatically a property of AANN's. Feed forward networks generally have poor extrapolation properties. Sensor failures have no precedent in the training set, therefore the networks estimate to an error in the input is unpredictable. An error introduced into a single sensor may be detected, but at the risk of compromising the remaining signals in the network. We know that an error has occurred in the system but we may not be able to isolate which sensor is faulted.

To achieve true robustness, specifically to produce a non-corrupted output value for inputs containing errors, the network must be trained on exemplars that represent the input/output behavior. To achieve the desired behavior, the original training set is augmented by new patterns with training inputs $X' = X + \delta I_j$ $j=1, \ldots\ldots m$ (m is number of input signals), I_j is the jth column of the identity matrix, and original target outputs Y. For each original training example, each sensor is corrupted several times using different random values of δ ranging between ± 10 percent of the original signal value. If there are n original training samples, there will be $2n$ samples in the robust training set.

Using the corrupted input set X', a robust network will be trained to produce the non-corrupted output Y.

A network trained using a robust training set forces the network to rely on all other parameters equally for a correct output estimate during a fault condition, instead of a select few.

5. SENSITIVITY ANALYSIS

Sensitivity is defined as the change of the output over the corresponding change in the input. Given the input vector x and output vector y:

$$S_x^y = \frac{\partial y}{\partial x}$$

The sensitivity analysis of the network is shown by a cumulative bar plot which shows the change in each of the networks outputs due to a 5% perturbation in each of it's inputs. One plot show s the sum of the output change for each signal and the other shows a normalized output change which indicates the contribution of each of the perturbed inputs in the network to the corresponding output change in each signal. This is shown by horizontal bars in each of the outputs.

Figure 2 shows the results of the sensitivity analysis for the non-robust trained network. For the non-robust case a perturbation of 5% in each input of the network results in a change in the output of between approximately 10% up to 900% with the contribution of other signals varying greatly to the overall change in each output (as noted by the 22 horizontal bars in each of the 22 signals). Due to the variation in the other network parameters in the network due to a small perturbation, the network could not perform well under input fault conditions.

The sensitivity results for a network trained with a robust training set is shown in Figure 3. A substantial improvement can be seen over the non-robust network. Each of the 22 outputs in the network respond equally to a 5% perturbation with the output sum change varying from 2% to 5%. We also note that the cumulation of sensitivities of each of the channels is approximately the same. Inputs 2 and 20 vary the most at approximately 5%. These signals (hotwell temps A and B) are the least linear correlated signals in the network. Thus, the sensitivity analysis proves to be a useful tool for network parameter selection. The robust network is stable to perturbations to the inputs, thus we would expect the robust network to perform well under input fault conditions. This is shown in a later section.

6. SEQUENTIAL PROBABILITY RATIO TEST (SPRT)

The SPRT technique, which was originally developed by Wald[9], uses a statistical method to determine if a sensor has failed. It does this by calculating the residual between a sensor's estimated value and its actual output and determining if this residual statistically significant: if the mean is more probably zero or some faulted setpoint. Rather than computing a new mean and variance at every new sample, the SPRT continuously monitors the sensor's performance by processing the residuals. This SPRT based method is optimal in the sense that a minimum number of samples is required to detect a fault existing in the signal.

The residual signals, which are the difference between the sensor measurements and the estimates from the trained autoassociative neural networks, are used to generate a likelihood ratio. When a sensor is operating correctly, the residual should have a mean of zero, and a variance comparable to that of the sensor (due to the filtering characteristics of an AANN). If there is sensor drift, the residual mean shifts. Due to the shift in residual mean, the likelihood ratio increases. If the likelihood ratio increases above a certain predefined boundary (user specified by false and missed alarm probabilities), the residuals are more likely to be from the faulted distribution than from the unfaulted distribution, and an alarm is initiated.

7. RESULTS

Two networks consisting of the signals listed in Table 1 with the same architecture (22-27-18-27-22) were created using different training methods. One network was trained using the standard non-robust training set and the other was trained using an augmented robust training set. Other than different training sets, all network parameters were the same. The two networks were compared using a sensitivity analysis, and a system simulation using a ISCV monitoring program created with SIMULINK[10] so that the response of all 22 signals could be monitored simultaneously. For the system simulation tests, a ramp error of +0.1% per day of the instruments maximum scale deflection was artificially created in sensor R234 ,reactor loop flow A.

7.1. SIMULINK ISCV monitoring program

To monitor the performance of the network the sequential probability ration test (SPRT)[11] was implemented using SIMULINK. The system block diagram is shown in Figure 4. The AANN estimate is compared to the measured signals and residuals are formed. The residuals are then sent to parallel (one for drift error detection, and one for gross error detection) SPRT blocks which output the status of each sensor (0 = good, 1 = bad) based on the variance of the residuals, a given faulted mean, a preset false alarm probability of 0.01% and a missed alarm probability of 10%. The faulted mean values were optimized using data that contained several transients. The output of the SPRT's are then processed by a logic filter with a 2 out of 4 delayed status voting scheme to eliminate false alarms due to spurious spikes in the plant data.

7.2. Network Simulation

Data for the test consisted of 4 days of full power plant operation sampled every 2 minutes, resulting in 2880 test patterns. Initially, a test was performed using plant data that contained several transients to verify that no false alarms occurred with error free plant data. A comparison of network performance was done to demonstrate the advantages of a robust training set. Finally, simulations were done to show the ISCV ability to detect drift as well as gross fault errors.

7.2.1. Robust vs. Non-robust Training

A simulation was performed using the non-robust trained network with an artificially induced drift of 0.1% of the instruments full scale deflection introduced into sensor 11 (reactor loop flow A). A residual variance of 0.01 (determined with MATLAB) with a faulted mean of 0.35 was used. The network did identify the drift in sensor 11 about 1 day into the drift (0.18% of the full scale value) but alarms in other channels at slightly greater times were also noticed (channels 4,10,12,15,17,19). This is in direct agreement with the sensitivity analysis results: a drift (perturbation) in the network input caused other parameters in the system to become vary. Although a drift was detected, the channel in which the drift occurred in is difficult to identify.

Figure 5 shows the results of the simulation using a network trained on a robust data set. We can see that the results are vastly improved. The network correctly identified the drifting sensor at approximately time interval 1250 and continued to detect the drift throughout the test with no false alarms recorded in other channels. The network correctly identified a drift at an error of 0.14% while the remaining channels in the system did not vary. The results are in direct agreement with the sensitivity analysis which showed that a robust trained network was insensitive to input perturbations. In addition to testing for faults in the above sensor (11) multiple test were performed on other sensors with similar results.

7.2.2. Drift Error Detection

A drift error is defined as a slow rate of change in a signals expected nominal value. To test the performance of the networks, both high and low drift faults of 0.1% per day of the instruments maximum scale value was artificially created in each of the 22 network channels. Simulations were performed to see how soon the AANN ISVC system could detected the fault with a minimum of false alarms. For each simulation, the time until the fault is first detected, the percent error of the drift (with respect to the full scale deflection of the signal) at the time of detection, and the number of false alarms in all the channels was recorded for both high and low drift fault scenarios. In each test case, faults were initiated at time zero.

Figures 5, 6, and 7 are plots of typical drift test cases in sensors R234 (reactor loop flow A), R212 (reactor outlet temp A), and R225 (reactor outlet pressure B) respectively. The top plot for each case shows the actual drifting signal and the neural network estimate (note the network filtering), the middle plot shows the residual between the two, and the bottom plot shows the SPRT fault hypothesis index. In all test cases, no false alarms were recorded. Table 2. below summarize the results for the three sensors. It list the computer point tag ID, the SPRT faulted mean value, the calculated residual variance, and the percent (of maximum scale deflection) detected drift error.

Table 2. Selected drift simulation results

Computer Pt. (Tag ID)	Set SPRT faulted mean	SPRT residual variance	% Detected drift error
R234	0.35	0.01	0.14
R212	0.2	0.006	0.15
R225	7.0	4.0	2.39

As the table shows, the system performed very well. The detection time generally depended on the noise level of the signal, the more noise, the longer the longer the detection times. The average detection time for a low noise sensor (temperature for example) was approximately 0.20% in less than a day. For a high noise sensor, (pressure) it increases to an average of approximately 2.4% in about one day. A minimum of false alarms was recorded. Throughout the entire testing scenario, only three false alarms were recorded, two of them in the same parameter (R200 -pressurizer level). This was primarily due to a sustained increase in noise in the signal for a 20 minute period in the test data.

On average, all parameters performed equally well despite of the fact that some were highly correlated within a network (reactor temperature) and some had practically no correlation at all (pressureizer level). This can be understood by the robust training method used. Robust training (faulted input/normal output) forces each parameter in the network to rely on all the other parameters equally, not just a select few (or possibly one as shown in the sensitivity plots).

7.2.3. Gross Error Detection

Gross faults are defined in this study as drastic changes in the parameters value. A plant scenario would be a circuit that opens or shorts, where all loss of information is encountered. Gross faults are simulated by failing the sensor to it's maximum or minimum full scale deflection, representing gross fault "high", or gross fault "low" respectively. Maximum and minimum scale deflection is listed for each parameter in Table 1.

Depending on how "gross" the signal fails, the other parameters in the network may, or may not vary. A large drop (or rise) in a signals value may cause other parameters in the network to vary in an attempt to compensate for such a large loss (or gain) of information. Experimental results have shown that a robust network can effectively compensate for a loss of approximately 25% of any one particular signal value. A larger fault can create false alarms in other channels due to the networks reliance on a select few parameters. The residuals may change to a degree that they are greater than the pre-set faulted mean values of the SPRT's. While the other parameter residuals may vary, it is only a fraction of the amount that the signal that contains the gross fault varies. For example, if we simulate sensor 4 as the gross failed sensor, then the residual for sensor 4 may be around 100, while the other variables are only around 10.

Since the drift detection SPRT's are optimized to detect incipient changes in the sensor, the obvious solution is a less sensitive SPRT. As can be seen in Figures 4 a "gross" detection SPRT block used for detection of gross sensor faults is used in parallel with the drift detection SPRT block. The gross SPRT's are identical to drift detection SPRT's except that they have faulted mean values that are considerably less constrained. The same variance values as the drift detection modules are used in the gross SPRT's.

The faulted mean values for the gross SPRT's were typically set to 15 times the drift fault means. Depending on the magnitude of the gross fault, some faulted means were set at higher value for optimal performance. The greater the fault, the more the other parameters in the network vary.

Like the drift test scenario, all variables were tested under gross fault conditions. Each variable was gross faulted high and low (max and min scale deflection values for each variable) with the time of detection and the number of false alarms in other channels recorded. In each case, the fault was initiated at time stamp 500, or 1000 minutes into the simulation.

Figure 8a shows an example of a signal gross fault low artificially created in sensor 9, (R222 Reactor outlet pressure A). At time sample 500, the sensor drops from it's median value of 2130 PSIG to it's minimum scale deflection of 1700 PSIG (drop of approximately 400 PSIG), with an associated change in residual mean of approximately 400 PSIG. This greatly exceeds the faulted mean value of the SPRT, thus an alarm is initiated at time sample 500 (immediately). Figure 8b shows the change of signal 16 (R224 Reactor outlet pressure B) due to the gross fault in sensor 9. A slight change in residual value can be seen when the fault was initiated (time sample 500), but not large enough to set off the SPRT due it's less stringent faulted mean setting. The residuals of the remaining 20 parameters during the gross fault condition changed to approximately ±10, less than their set faulted means. Thus the system accurately detected a gross fault in sensor 9 with no false alarms recorded in other channels.

8. CONCLUSIONS

The results of this study have shown that a plant wide sensor calibration monitoring system using autoassociative neural networks is not only feasible but very practical.

A methodology has been described to implement such a system. This includes parameter selection utilizing linear correlation coefficients and sensitivity analysis, a feature detection network architecture, and a fast reliable training method to create a robust network.

To detect the faults, a drift and gross fault detection system has been implemented using the sequential probability ratio test (SPRT). The complete ISCV system has been integrated using Matlabs SIMULINK software.

The SPRT detection module proved to be an excellent detection tool for incipient drift faults as well as gross faults. Results show that the ISCV system using autoassociative neural networks could clearly detect a fault or drift in a single channel without affecting the other channels being monitored. Thus the network not only detects the fault, but isolates the channel in which the fault has occurred.

ACKNOWLEDGMENTS

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Table 1. Selected network Parameters

Network B Signals								
Sensor #	Tag ID	Signal Description	Units	Tech Spec	Redundant	Variance	Median	Range
1	R214	Reactor Pump Suction Temp - A1 (Narrow)	DEG F			0.008	557.8	520-620
2	R215	Reactor Pump Suction Temp - A2 (Narrow)	DEG F			0.009	557.5	520-620
3	A216	Hotwell Temp - A	DEG F			0.118	112.8	32-220
4	P208	Linear Power Channel NI - 5	PERCENT		P209,P210,P21	0.021	100.5	0-125
5	R200	Pressurizer Level (L1) (Uncomp)	INCHES	YES	R201,R202	0.107	143	0-320
6	R208	Reactor Pressure - A (Wide)	PSIG	YES	R209	3.758	2139	0-2500
7	R209	Reactor Pressure - A (Wide)	PSIG	YES	R208	4.119	2141	0-2500
8	R212	Reactor Outlet Temp - A (Narrow)	DEG F	YES	R226,R227	0.005	600.5	520-620
9	R222	Reactor Outlet Pressure - A (Narrow)	PSIG	YES	R223	3.758	2129	1700-2500
10	R223	Reactor Outlet Pressure - A (Narrow)	PSIG	YES	R222	3.397	2137	1700-2500
11	R234	Reactor Loop Flow - A (CH A)	MLB/HR	YES	R236,R238,R240	0.008	74.1	0-80
12	R327	T-hot Loop - A	DEG F	YES		0.047	601.2	120-920
13	R328	T-hot Loop - B	DEG F	YES		0.043	600.3	120-920
14	R210	Reactor Pressure - B (Wide)	PSIG	YES		4.067	2162	0-2500
15	R213	Reactor Outlet Temp - B (Narrow)	DEG F	YES	R228,R229	0.014	600.9	520-620
16	R224	Reactor Outlet Pressure - B (Narrow)	PSIG	YES	R225	3.339	2151	1700-2500
17	R225	Reactor Outlet Pressure - B (Narrow)	PSIG	YES	R224	3.421	2134	1700-2500
18	R235	Reactor Loop Flow - B (CH A)	MLB/HR	YES	R237,R239,R241,	0.005	72.7	0-80
19	E202	Unit 3 Electrical Generation	MW			1.962	875.7	0-1200
20	A217	Hotwell Temp - B	DEG F			0.169	116.4	32-220
21	R216	Reactor Pump Suction Temp - B1 (Narrow)	DEG F			0.008	557.8	520-620
22	R217	Reactor Pump Suction Temp - B2 (Narrow)	DEG F			0.008	558.5	520-620

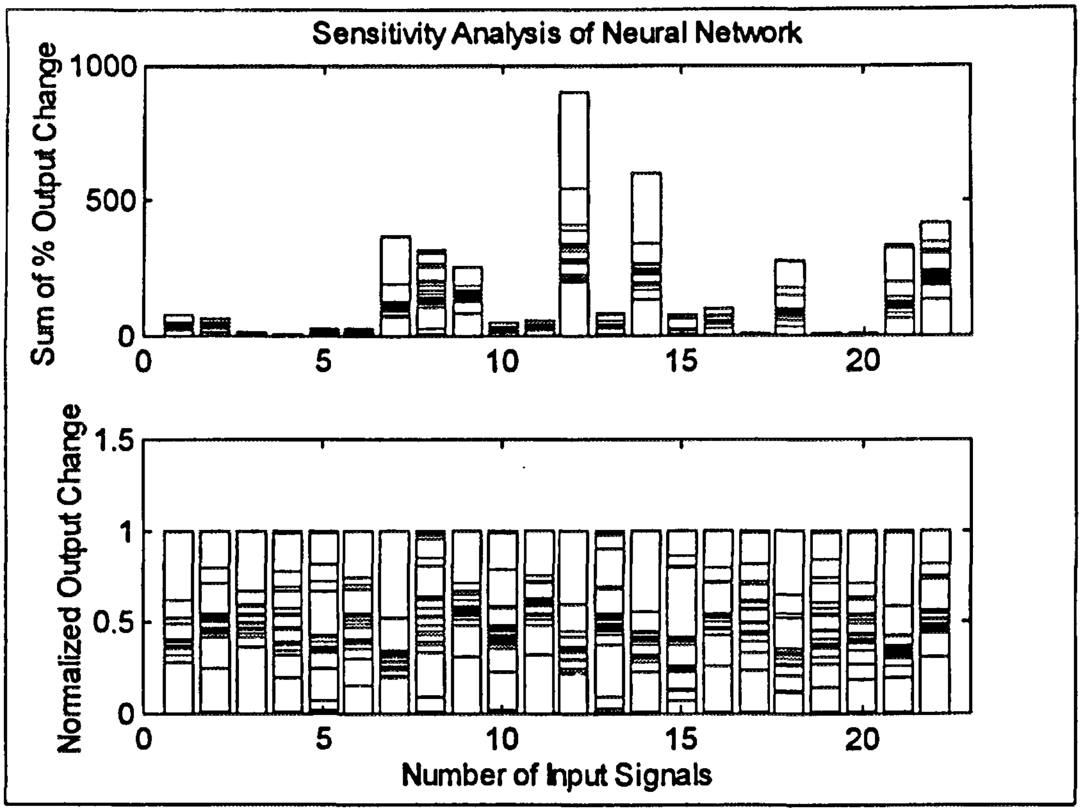

Figure 2. Sensitivity analysis of network trained with non-robust training set when a 5% perturbation is introduced into each of the inputs

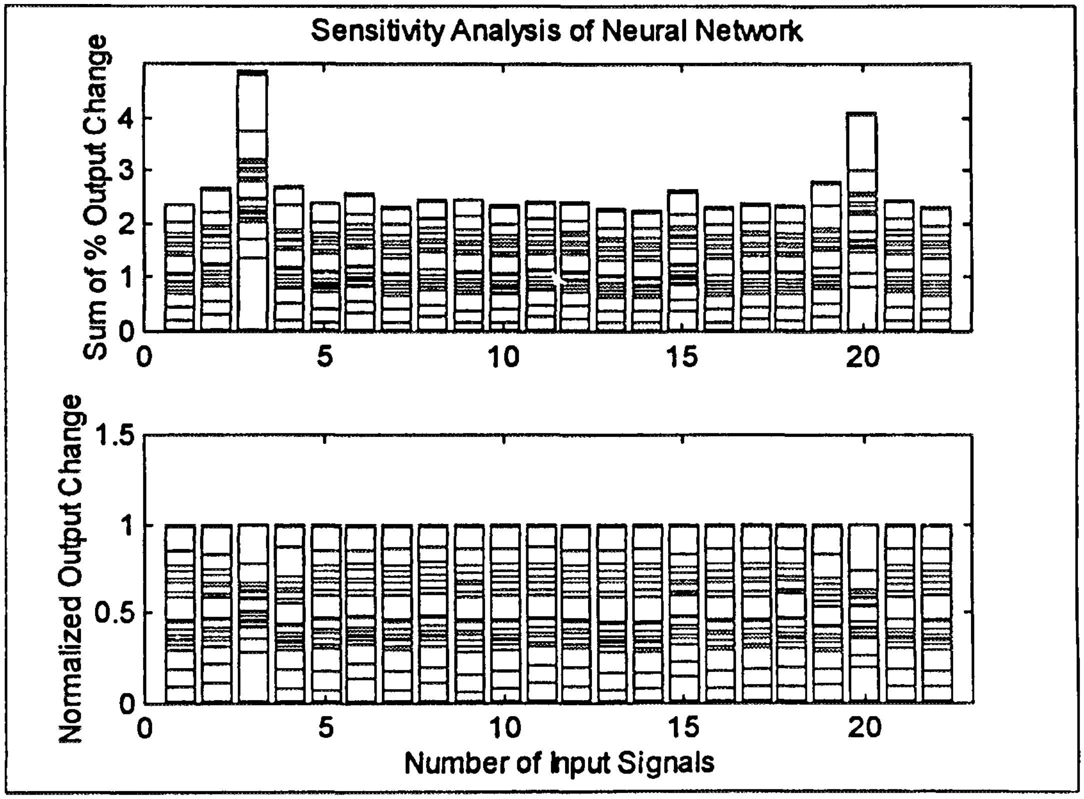

Figure 3. Sensitivity Analysis of network trained with robust training set when a 5% perturbation is introduced into each of the inputs

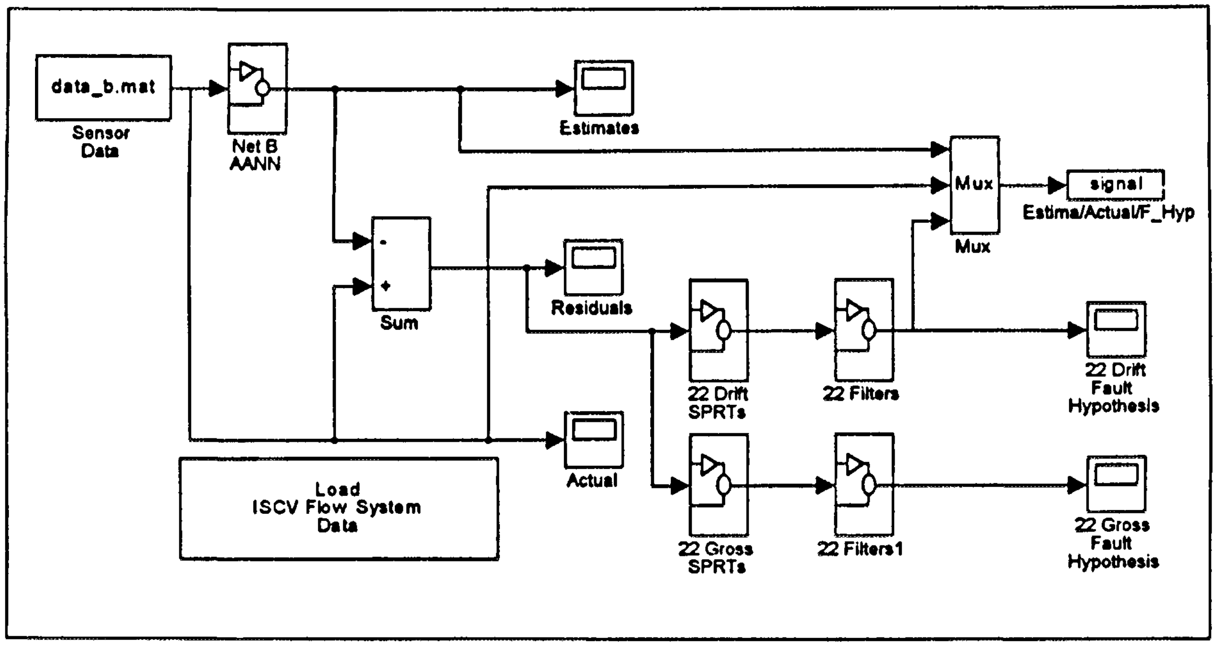

Figure 4. SPRT ISCV monitoring system

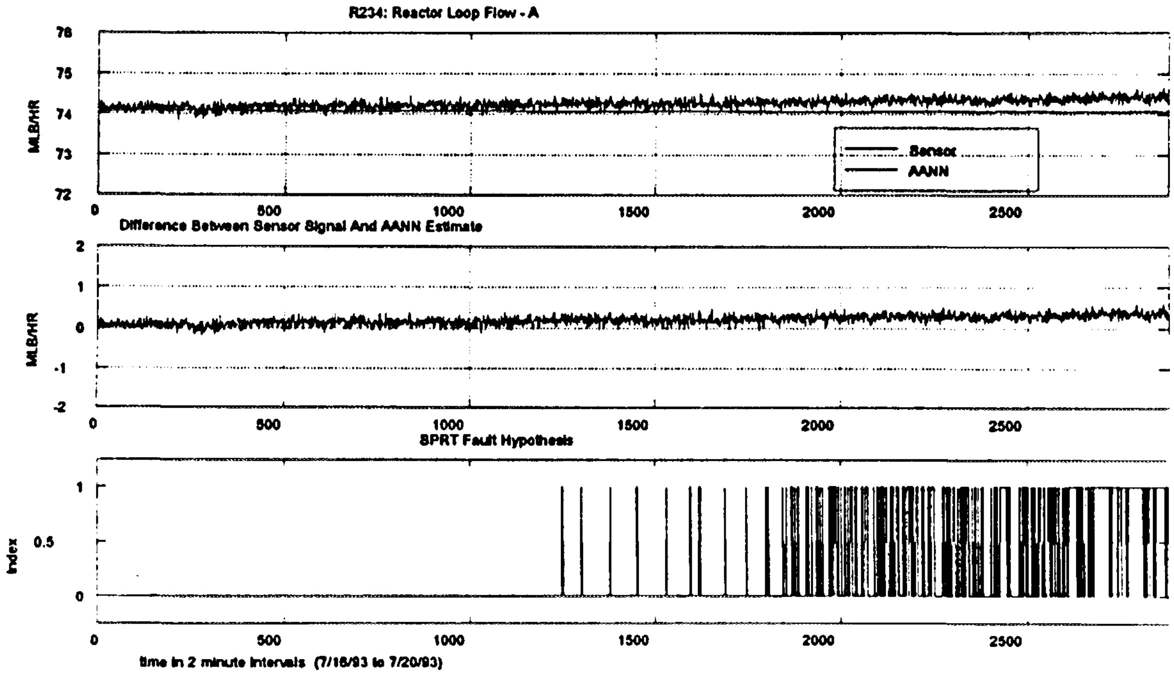

Figure 5. ISCV system detecting a fault drift high in the reactor loop flow when a drift of 0.1% per day of the instruments maximum scale deflection is introduced into the sensor signal

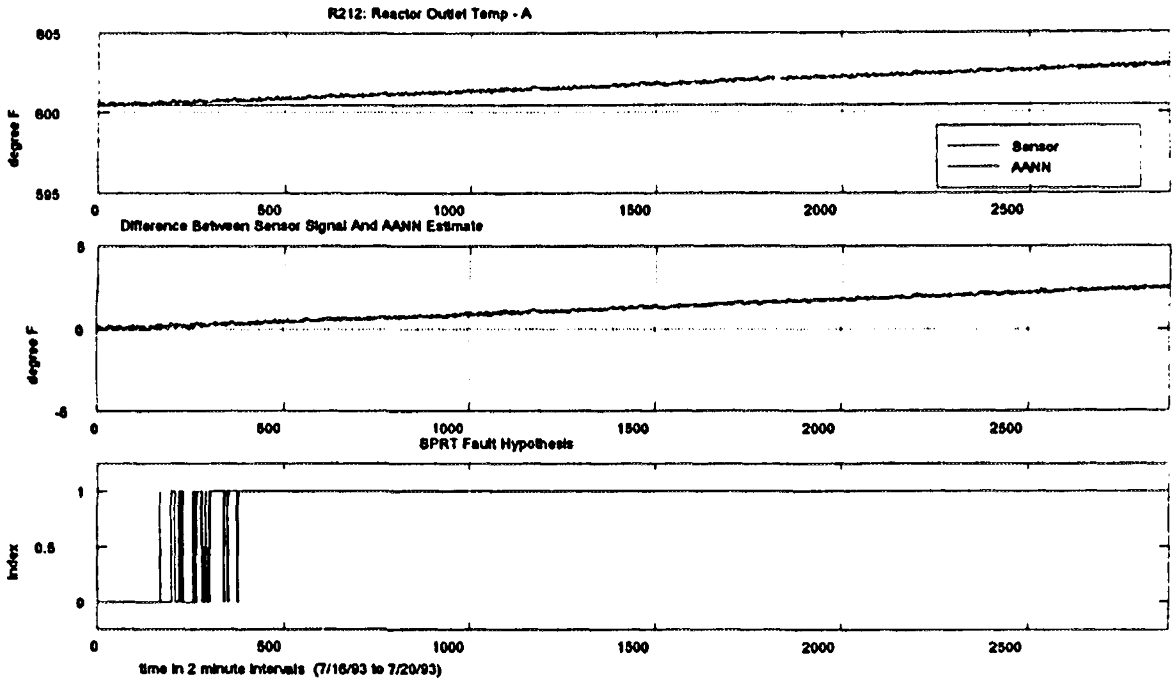

Figure 6. ISCV system detecting a fault drift high in the reactor outlet temperature when a drift of 0.1% per day of the instruments maximum scale deflection is introduced into the sensor signal

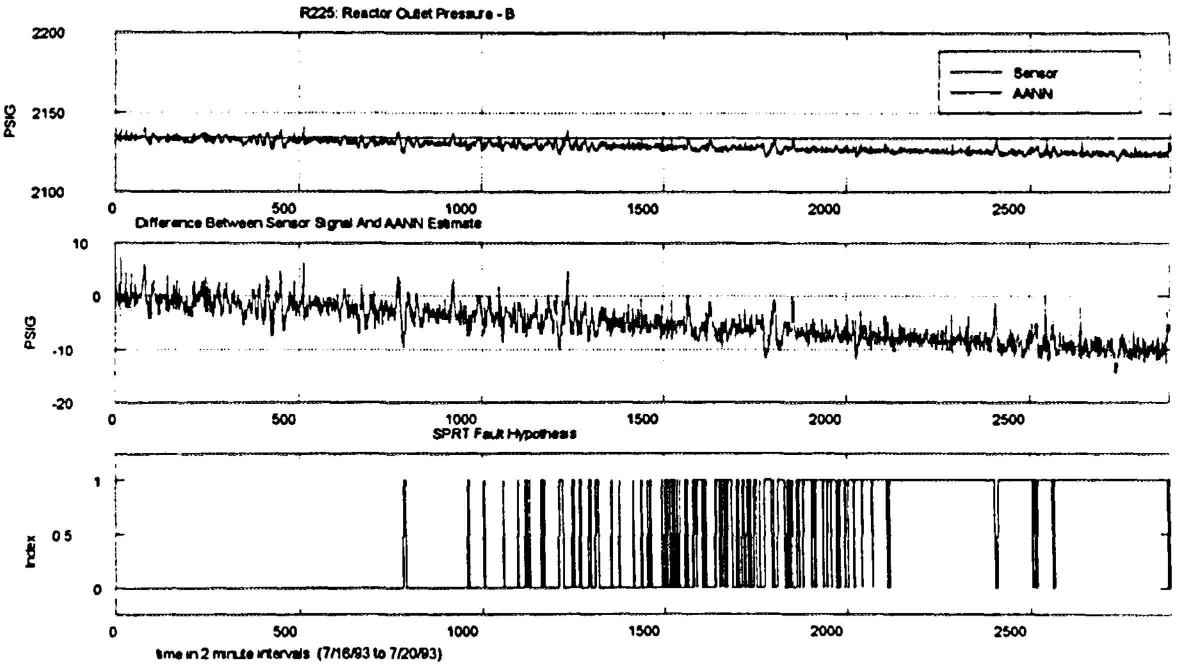

Figure 7. ISCV system detecting a fault drift low in the main steam pressure when a drift of 0.1% per day of the instruments maximum scale deflection is introduced into the sensor signal

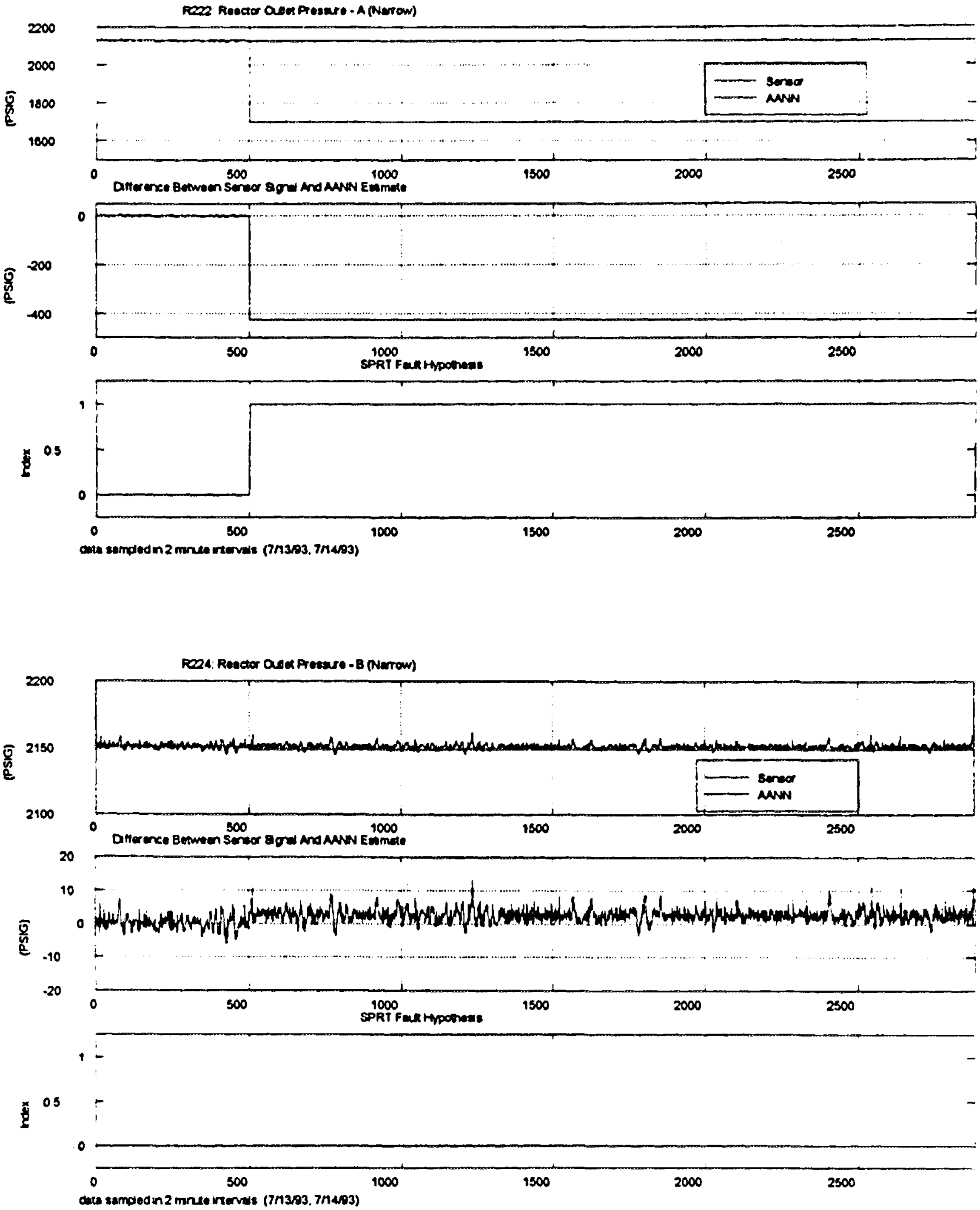

Figure 8. Response of "gross" fault initiated at time sample 500 a.) variable gross fault was initiated in b.) typical response of companion network variable

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DEVELOPMENT OF NUCLEAR POWER PLANT MONITORING SYSTEM WITH NEURAL NETWORK USING ON-LINE PWR PLANT SIMULATOR

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ABSTRACT

The purpose of this paper is to demonstrate a nuclear power plant monitoring system using artificial neural network (ANN). The major advantages of the monitoring system are that a multi-output process system can be modelled using measurement information without establishing any mathematical expressions. The dynamics model of reactor plant was constructed by using three layered auto-associative neural network with backpropagation learning algorithm. The basic idea of anomaly detection method is to monitor the deviation between process signals measured from actual plant and corresponding output signals from the ANN plant model. The simulator used is a self contained system designed for training. Four kinds of simulated malfunction caused by equipment failure during steady state operation were used to evaluate the capability of the neural network monitoring system. The results showed that this monitoring system detected the symptom of small anomaly earlier than the prevailing alarm system.

1. INTRODUCTION

The condition monitoring in a nuclear reactor is of major concern during operation. This is primarily because of the operational safety which is directly related to the operation and maintenance cost. The usual monitoring method is to set the fault threshold level for each plant parameter and to alert when the monitored signal exceeds its threshold level. However, when anomalies are detected, they are possibly too developed to cope with. Therefore, it is necessary to develop model-based monitoring methods to detect symptoms of anomaly.

For a complex and non-linear system, like a nuclear power plant, system modeling is a formidable task if many reasonable approximations and simplifications are not tolerated. Nowadays there are a number of computer codes based on physical and mathematical models for nuclear power plant monitoring, but they don't have sufficient capability to diagnose plant conditions over wide power range, including transient operation, and to work in real time. In this respect the use of artificial neural network (ANN) has a great benefit to the power plant monitoring, apart from other numerous application areas[1,2].

We developed an ANN on-line plant wide monitoring system for Borssele NPP in the Netherlands[3,4]. The present work is an attempt to evaluate the usefulness of the monitoring system by using an on-line plant simulator, in order to simulate many kinds of abnormal operation.

2. HARDWARE CONSTRUCTION

2.1 Data flow in the Monitoring System

The simulator is connected to an on-line data acquisition system in PC. The analog output signals are digitized in PC, and sent to WS in real time by local area network (LAN). The neural network and real-time expert system for plant monitoring are programmed in WS[5,6]. The construction of the monitoring system is shown in Fig. 2.1.

2.2 PWR Plant Simulator

The simulator is a self contained system designed to train power plant personnel in the general principles of a typical pressurized water reactor (PWR) plant. It is composed of a control desk containing a process mimic display panel and a control panel, an instructor console, control console and a general purpose digital computer. Totally 88 analog signals of plant parameter are picked out from the mimic panel and the eight channel pen recorder.

The simulator is manufactured on the basis of an existing 822 MWe power plant, Surry-1, USA. There are three primary coolant loops with three typical U-tube steam generators (SGs). We can take into consideration in 15 different plant initial states covering from cold shutdown to full power, and 49 malfunctions of major system including failure of pumps, valve, controllers, pipes, etc.

Figure 2.2 shows the simplified schematic representation of Surry-1 NPP and selected process signals for plant monitoring. The process signals are selected from loops B and C, only where the triggers of malfunctions are limited .

3. NEURAL NETWORK MODEL

3.1 Multi-layer Feedforward Neural Network

In the multilayer feedforward network, all neural signals propagate in the forward direction through each network layer from the input to output layer, and no lateral, self and backward propagation is allowed. Given a set of inputs, the output of the neuron is computed in a forward path which computes in turn the activity levels of neurons in each layer using the already computed activity levels in the preceding layers. Here the sigmoidal logistic function representing continuous and nonlinear activation is selected as the activation function.

3.2 Back Propagation Algorithm for Training

Training of the networks is now performed using the error back propagation scheme which evolves a set of weights to produce a mapping from the input to the output[7]. This training procedure involves the presentation of a set of the input and output patterns to the network. The network first uses the input values to compute its own output values, and then compares the computed outputs values with the desired ones. If there is no error between them, no change takes place. Otherwise the weights of connections are changed to reduce the error using the following equations.

$$W_{i,j}^{k-1,k}(t) = W_{i,j}^{k-1,k}(t-1) + \Delta W_{i,j}^{k-1,k}(t) \qquad (1)$$

Here $W_{i,j}^{k-1,k}$ is the weight for the signal from the neuron i in the (k-1)th layer to the neuron j in the k-th layer; t indexes the presentation number of learning cycle.

$$\Delta W_{i,j}^{k-1,k}(t) = \eta\delta_j^k \times O_i^{k-1} + \alpha \cdot \Delta W_{i,j}^{k-1,k}(t-1) \qquad (2)$$

where δ_j^k is an error signal; O^{k-1}_i is the output of neuron i in the (k-1)th layer; η is the learning rate; α is a constant which determines the effect of past weight change. The third part of equation (2), called momentum term, is often useful to escape from local minimum and offer the rapid learning. In this application, η and α become smaller from 1.2 till 0.1 in stages during learning.

3.3 Network Structure

For neural network utilization 12 plant signals are picked out as shown in Fig. 2.2: they are ex-core neutron flux (EX-CORE), generated electric power (GEP), hot-leg temperature in primary loop-B (HLTL2) and loop-C (HLTL3), primary water flow (PWF), feedwater pressure (FWP) and steam pressure (SG2SP and SG3SP), steam flow (SG2SF and SG3SF) and feedwater flow (SG2FWF and SG3FWF) of secondary loop-B and loop-C. These signals are most significant and selected with reference to the monitoring system for Borssele NPP. It is important to note that hot-leg temperature is used as temperature information of primary system, because cold-leg temperature is almost stable from 20 % to 100 % power. A feedforward neural network has been trained in auto-associative mode with plant's operational data in wide-range.

The neural network has three layers, an input layer, one hidden layer and an output layer as shown in Fig. 3.1. The three layers are composed of 12 input nodes, 8 hidden nodes and 12 output nodes, respectively. Output signals are the same as input signals. Here all input nodes are fully connected to all hidden nodes. Likewise all hidden nodes are also fully connected with output nodes. This neural network is programmed in FORTRAN and connected to real-time expert system on WS, Sparc20.

The initial values of weights are randomly selected to characterize each neuron of the hidden layer. All input data are normalized so as to be in the range from -0.5 to 0.5, and output data are normalized from 0.1 to 0.9.

The learning data are obtained from three different power level at the beginning of fuel period. One hundred serial points data sampled every 1 s at 20, 50 and 100 % power are respectively picked out. The total number of patterns for the learning is 300. The neural network iterates 1000 times per each pattern. The patterns are given randomly within each learning cycle. It takes less than one minute on Sparc20.

After initial learning, the fault severity levels (ε_f) for the deviation between measured and estimated signal is empirically defined as

$$\begin{aligned} \varepsilon_f &= 1.25\,\varepsilon_{max} \quad (\varepsilon_{max} \geqq \varepsilon_{sd}) \\ \varepsilon_f &= 1.25\,\varepsilon_{sd} \quad (\varepsilon_{max} < \varepsilon_{sd}). \end{aligned} \tag{3}$$

Here maximum error ε_{max} is defined as the largest deviation during initial learning, and ε_{sd} is twice of standard deviation at stationary full power normal operation. In the present case, ε_{sd} of Primary Water Flow, and Steam Pressure in loop B and C are larger than its maximum error. Table 3.1 summarizes fault severity levels of each signals.

3.4 Sensitivity Analysis by ANN

On whole, since the inner construction of the network is not clear, it must be used only as black box. Here we try to understand the construction of the neural network and evaluate the network modelling by sensitivity analysis. The sensitivity is defined as a change of the output over the corresponding change at the input. The neural network can model the outputs with inputs by learning.

The input vector is $\mathbf{x}$ and output vector is $\mathbf{y}$.

$$\mathbf{y} = f(\mathbf{x})$$
$$y_j = f_j(x_1, x_2, \ldots, x_l)$$

Here f(x) is the function modeled by neural network; l is the number of input nodes and n is the number of output nodes. The sensitivity of output y_j over the change at the input x_i is calculated as

$$\frac{\Delta y_j}{\Delta x_i} = \frac{f_j(x_1,x_2,\cdots,x_i+\Delta x_i,\cdots,x_I) - f_j(x_1,x_2,\cdots,x_i,\cdots x_I)}{\Delta x_i}, \tag{4}$$

where Δx is a small perturbation added to the input. The contribution of the input x_i to the output y_j is defined as

$$P_{ji} = \frac{\dfrac{\partial y_j}{\partial x_i}}{\sum_{k=1}^{I} \dfrac{\partial y_j}{\partial x_k}} \times 100 \quad (\%). \tag{5}$$

The sensitivity analysis using one hundred points of only for 100 % power data in learning patterns were shown in Fig. 3.2. Here 5 % perturbation is added to each input. The result for 10 % perturbation is almost same as previous analysis. Furthermore, the results of sensitivity analysis with 20 % or 50 % power data are also similar. From these results, the calculated cumulation of sensitivity in Fig. 3.2 is accurately calculated.

Input signals of Ex-core, Feedwater Pressure and Feedwater Flow in loop B and C influence all output signals in general. On the other hand, the contributions of itself signal are around 15 %, and those are not so large except channel 3 (Primary Water Flow; PWF). The self contribution of PWF is more than 50 %, furthermore the cumulation to other signals is small. It can be said that PWF signal is not satisfactorily modeled by neural network, because PWF signal is always stable from 20 % to 100 % power range. However such kind of signals can be sufficiently monitored with simple fault severity level as prevailing method. This sensitivity analysis is consequently effective to evaluate the modeling by neural network.

4. MONITORING TESTS

Using the simulator, four kinds of malfunctions caused by equipment failure during steady state operation were simulated here. These abnormal conditions are loss of reactor coolant system flow, feedwater system failure, leakage of atmospheric steam dump valve and detector failure of volume control tank level. During operating condition at full power, all malfunctions were added after 9 s. The data obtained from the abnormal conditions were used to evaluate the capability of the neural network monitoring system.

The results of three malfunction cases are shown in Figures 4.1-4.3. The solid line in the figures indicates the measured signals from the simulator. The dotted line represents the estimated values by neural network. The diamonds indicate the deviation between measured signals and estimated values. Two horizontal broken lines show the fault severity levels for monitoring. This level is defined by initial learning as mentioned in forgoing chapter. When the deviation is in the range between two horizontal lines during monitoring, the plant condition should be considered normal. If the deviation exceeds the limit, the monitoring system alerts anomalies. Table 4.1 summarizes the comparison of anomaly detection time by neural network monitoring system and the prevailing alarm system.

4.1 Partial Loss of Feedwater

This malfunction is tube failure in the first point heater, where the highest pressure point in secondary loop is given. Partial loss of feedwater causes a decrease of feedwater flow rate and pressure. Reactor control system perceives decreasing of feedwater, and the feedwater control valve is opened fully to increase feedwater from other loops. However, the level of steam generator is slowly decreasing. Because the leak is small in this case, no alarm was sounded in ten minutes after the malfunction started.

On the other hand, the monitoring system found this anomaly at 2 s after the malfunction started, with the deviation of feedwater pressure exceeding the fault severity level owing to rapid decrease of feedwater pressure and flow rate, as shown in Fig. 4.1. Feedwater flow of B and C loops indicated anomaly after 3 s.

4.2 Leakage of Atmospheric Steam Dump Valve

During full power operation, atmospheric steam dump valve seat leakage of 100 % valve capacity occurred. The steam leakage from atmospheric steam dump valve caused rapid decrease of steam flow and pressure. Furthermore those simultaneously induced the average steam temperature decrease and the power decrease. To supplement the loss of power, the control rod was driven out by control system. However, because of over reactor power by rod withdrawing, "rod stop" alarm was given 30 s after malfunction started. The monitoring system detected anomaly of all signals without primary water flow at 4 s after malfunction, as shown in Fig. 4.2.

4.3 Partial Loss of Reactor Coolant System Flow

Reactor coolant pump C shaft locked during full power operation. Partial loss of flow (C loop) was due to loss of Impeller. Reactor coolant system flow in C loop dropped rapidly in 2 s, Reactor tripped at 92 % primary water flow after 2 s. While eight other alarm were also sounded in 5 s, neural network monitoring system found this anomaly in 4 s. This malfunction is much more severe than previous two cases, and there was no obvious difference between the neural network monitoring and the prevailing alarm system.

4.4 Volume Control Tank (VCT) Level Control Fails Low

During full power operation, VCT level fails zero scale with alarm. Because of level controller failure, the VCT outlet valve shut and the charging water from Refueling Water Storage Tank (RWST) was supplied to the reactor coolant. Borated water from RWST causes average temperature to decrease, so that control rods stepped out to increase average temperature. Eventually, rod withdraw limit alarm was given after 720 s.

Because the plant condition continued to be normal at the beginning of malfunction, it takes 24 s for the neural network monitoring system to detect this plant anomaly. As Fig. 4.3 indicates, the monitoring system found an anomaly of ex-core neutron flux at 24 s because of neutron flux decreasing by boron injection. After 100 s, the deviation of hot-leg temperature at loop B and C also exceeded the fault severity levels because of temperature decreasing. From this result, it might be said that the combination of neural network monitoring system and prevailing alarm can easily diagnose such kind of sensor errors.

5. CONCLUSIONS

The study demonstrates that the monitoring system with the neural network successfully detects a various kinds of anomalies in the early stage of malfunctions by using PWR plant simulator. The use of the ANN promises to be an effective way of developing a powerful monitoring system, and may ensure the safety of the commercial nuclear power plants.

In the next step, integration to an expert system will be required to realize the desirable coordination of human-machine interface. In addition, we have to accumulate deviation patterns of anomaly condition for the database of expert system. Final goal is to detect all kinds of anomalies in early stage, and in real-time.

ACKNOWLEDGMENTS

The authors wish to acknowledge Dr. T. Suzudo and Dr. K. Hayashi for their helpful advice.

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Table 3.1 Fault Severity Level

Ch No.	Plant Signal (Unit)	Max. Error (ε_{max})	S.D. x 2 (ε_{sd})	Fault Severity Level (ε_f)
1	EX-CORE (%)	0.567	0.158	0.709
2	FWP (kgf/cm^2)	0.4984	0.1140	0.6230
3	PWF (x10^3 ton/hr)	0.0084	0.1224	0.1530
4	HLTL2 (°C)	0.2782	0.1498	0.3477
5	HLTL3 (°C)	0.2887	0.1406	0.3609
6	SG2FWF (ton/hr)	50.558	5.828	63.198
7	SG3FWF (ton/hr)	51.773	5.707	64.717
8	SG2SP (kgf/cm^2)	0.1213	0.1443	0.1803
9	SG3SP (kgf/cm^2)	0.1166	0.1503	0.1879
10	SG2SF (ton/hr)	9.518	1.324	11.898
11	SG3SF (ton/hr)	10.470	1.692	13.088
12	GEP (MW)	8.880	4.076	11.101

Table 4.1 Comparison of Anomaly Detection Time

Malfunction	Prevailing Alarm System	Neural Network Monitoring System
Partial Loss of Feedwater Flow	NO ALARM	2 sec: Feedwater Press. Error 3 sec: Feedwater Flow(B) Error 3 sec: Feedwater Flow(C) Error
Leakage of Atmospheric Steam Dump Valve	30 sec: ROD STOP	4 sec: All signal Error without Primary Water Flow
Partial Loss of Reactor Coolant System Flow	2~5 sec: REACTOR TRIP, etc	1 sec: Primary Water Flow Error 4 sec: Electric Power Error 5 sec: All signal Error
VCT Level Control Fails Low	0 sec: VCT LEVEL LOW 720 sec: ROD WITHDRAW LIMIT	24 sec: Ex-core Neutron Error 102 sec: Hot-leg Temp.(B) Error 103 sec: Hot-leg Temp.(C) Error

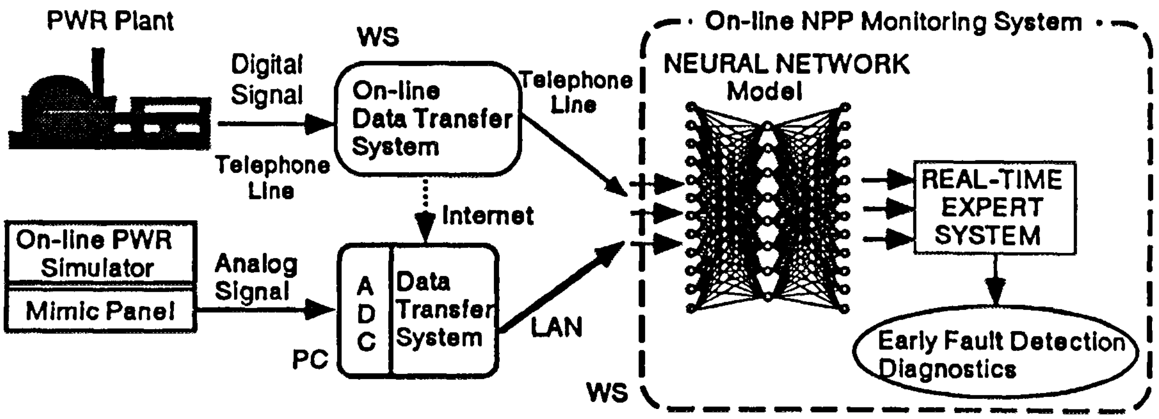
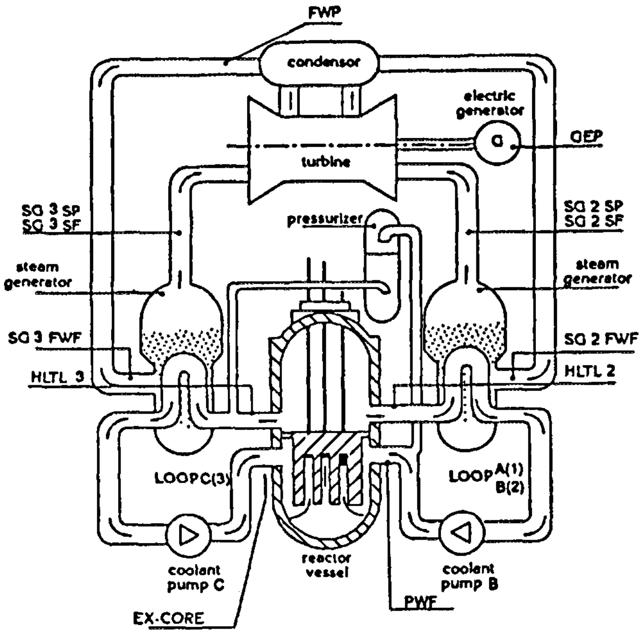


Fig. 2.1 Monitoring System Construction



EX-CORE: ex-core neutron flux
FWP : feedwater pressure
PWF : primary water flow
HLTL2 : hot-leg temp. in primary loop-B
HLTL3 : hot-leg temp. in primary loop-C
SG2FWF : feedwater flow of secondary loop-B
SG3FWF : feedwater flow of secondary loop-C
SG2SP : steam pressure of secondary loop-B
SG3SP : steam pressure of secondary loop-B
SG2SF : steam flow of secondary loop-B
SG3SF : steam flow of secondary loop-C
GEP : generated electric power

Fig. 2.2 Schematic Representation of PWR Plant Simulator

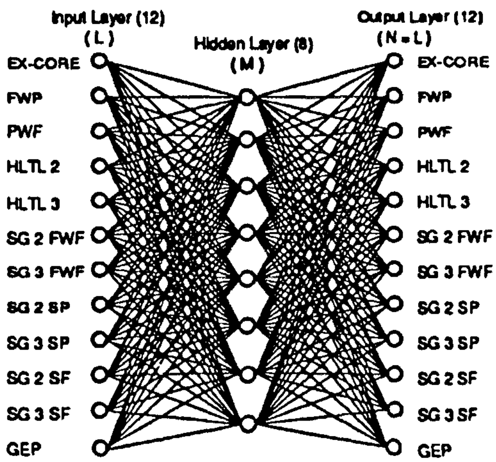


Fig.3.1 Auto-associative Neural Network Model

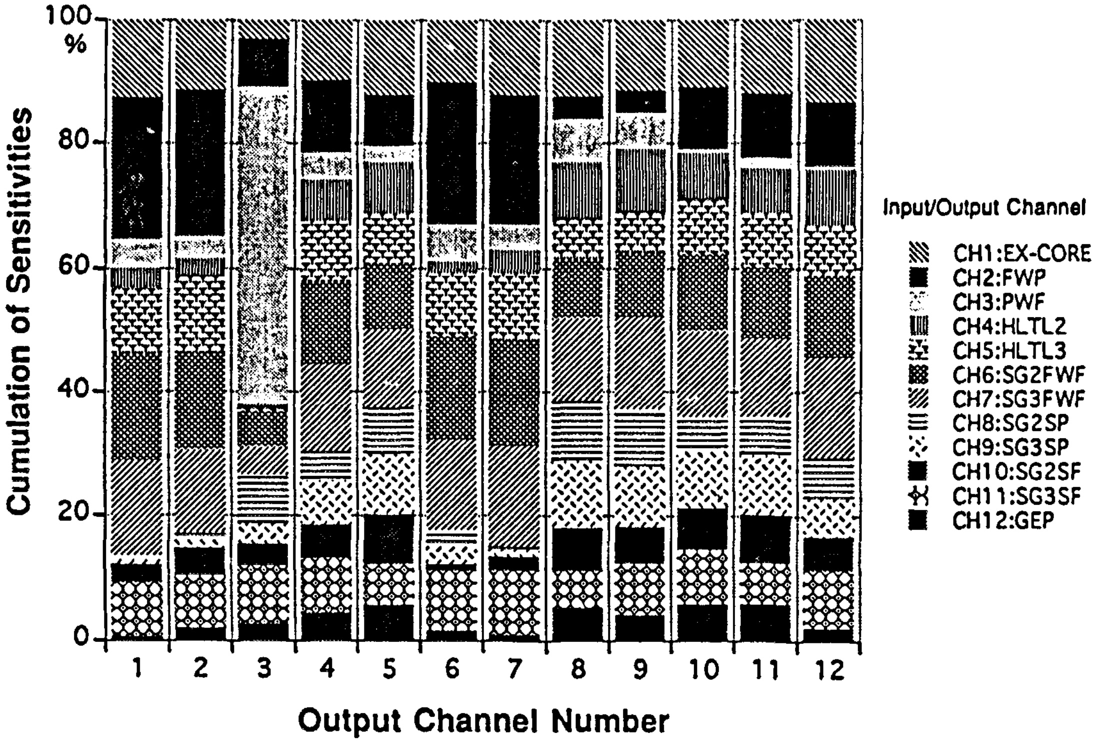


Fig. 3.2 Contribution of Measured Signals to Estimated ANN Output Channel

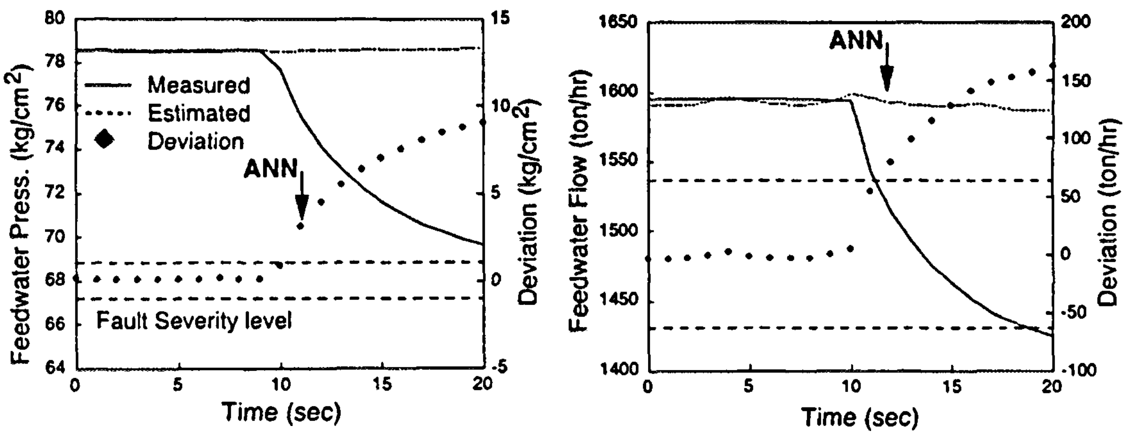


Fig. 4.1 Results in Case of Partial Loss of Feedwater (No Alarm is given)

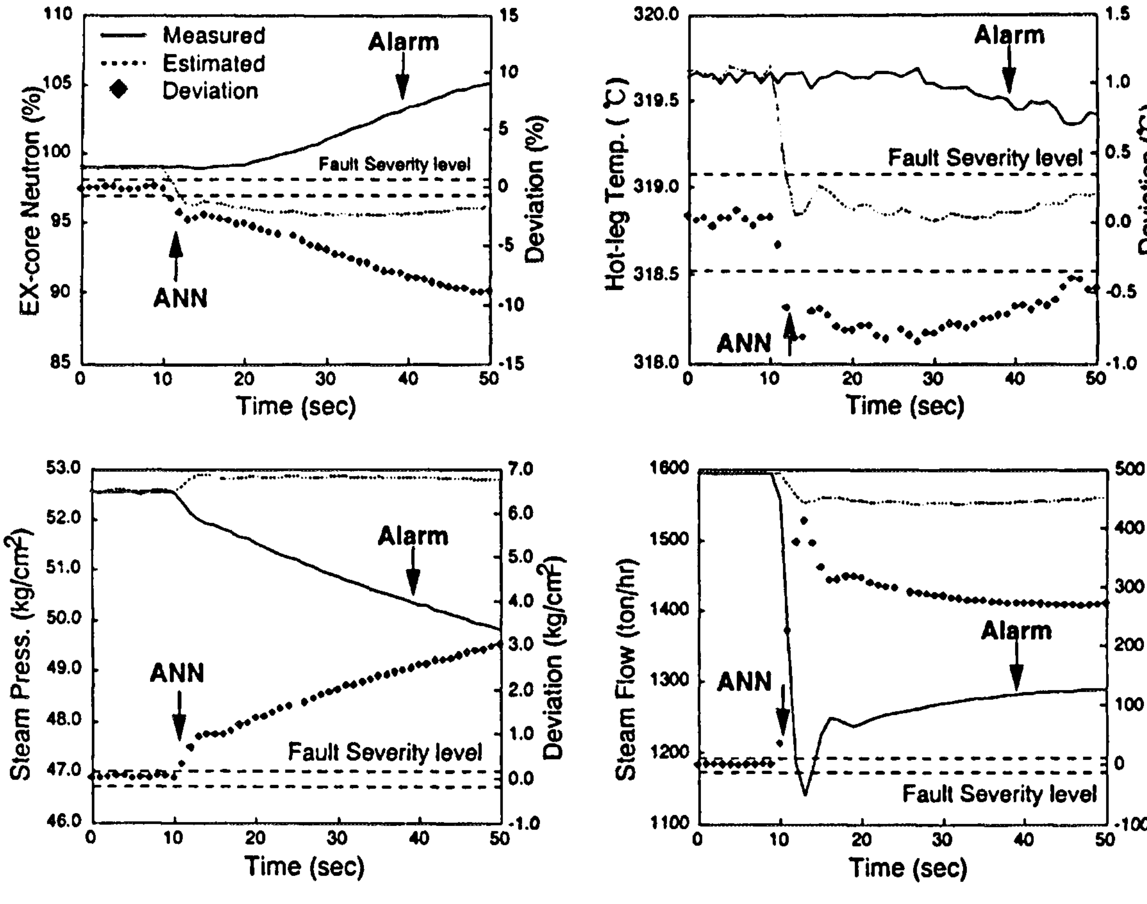


Fig. 4.2 Results in Case of Leakage of Atomospheric Steam Dump Valve

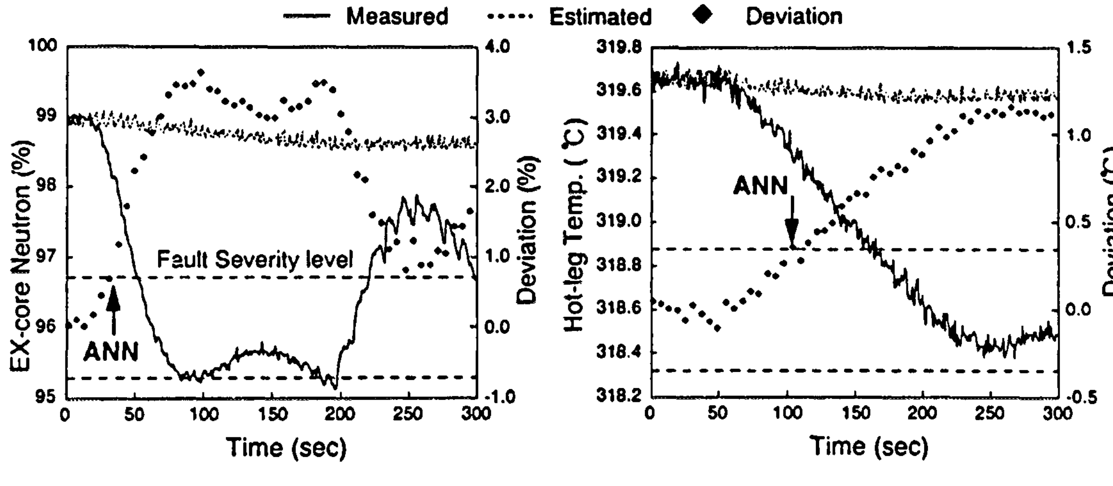


Fig. 4.3 Results in Case of VCT Level Control Fails Low (Alarm is given after 720 s)

XA9743574

AN OBJECT-ORIENTED-DATABASE-SYSTEM TO ASSIST CONTROL ROOM STAFF

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Keywords. *OODBS-System, control room staff assistance, reliability, failure history/statistics, bitmap files, technical drawings, part lists.*

Abstract. *In order to assist control room staff in case of failure of any electrical or mechanical component a new object-oriented-database-system (OODBS) has been developed and installed. Monitoring and diagnostics may be supported by this OODBS within a well-defined response time. The operator gets a report on different levels: For example, at a first level data about the vendor of a device (like reactor vessel internals, pumps, valves, etc.), date of installation, history of failures since installation, at a second level e.g. technical data of the device, at a next level e.g. a scanned photo of the device with its identificaiton number within a certain compartment, and at another level using a CAD-system presenting technical drawings and corresponding part lists in order to assist necessary communication between operator and maintenance technician.*

1. INTRODUCTION

Object-oriented databases were introduced in the late 1980s to provide database management for applications built using object technology. Object technology enhances traditional application development by introducing new data modeling and programming techniques. To achieve *better maintainability*, object technology organizes *code into objects*, which *combine data and procedures*. This introduces significant database issues, since the object model is different in many respects from traditional data models.

Databases using object-oriented technology have become the preferred solution for applications requiring the storage and processing of complex data. Conventional relational database management (RDBM) schemes are unable to model the complex constructs and processes found in some fields like engineering environment. Complex assemblies, versions, and revisions of elaborate product configurations, variant and multiple product structures, concurrent engineering environments, and global design-to-manufacture business control are too complex, too dynamic, and too widely distributed to be easily implemented with RDBM systems.

Object-oriented technology has become the technology of choice for complex data and processes, because object-oriented systems

- can easily model complex data,
- demonstrate much faster performance,
- support an unlimited number of atomic types,
- move or seperate information into component parts,
- support facilities for managing the notion of time, versions of objects and schema, and change notification,
- scale to larger networks with higher system availability.

This is functionality that is difficult or impossible to obtain with relational database management systems.

Blobs and Stored Procedures = OBJECTS

Several relational database management system vendors perseived years ago that they needed to extend their products past the basic relational model. Two common extensions have been *blobs* (binary large objects) and stored procedures. Without blobs , most relational databases could store only fixed-length fields of certain predefined types (e.g. INTEGER, REAL, CHARACTER). With blobs, a relational database can also store variable-length unformatted data, basically treating that data as bit strings. An important use of blobs has been to enable relational databases to store images.

Object-Oriented Database Management System

One of the most interesting properties of object-oriented programming languages is inheritance. Using this feature a programmer is able to establish a hierarchy among different classes. A child class simply inherits the whole or a part of the properties of its parent class(es). Defining a class with data members that are also classes is another way of making relations between classes.

Using a relational DBMS does not support the programmer in the form of taking over the whole data structure and functionality into the database. In some cases, even the data structure has to be taken apart into the native types of the relatinal DBMS and stored in a different scheme. This translation would destroy the data structure.

Having the same data structures and functionality in the data base system as well as in the application can become very important, specially during the analyzation phase, when the analyst has to model the data structures and classes that should be used in the application. Object-oriented databases make this feature possible for analysts. Classes and their logic can be taken over directly into the database without having to translate them into a limited number of data types that are relevant in the relational database systems. This would make the process of abstracting complex models easier for both analyst and software developer as well.

An object-oriented database system is also able to store the relations between the classes. This is important because using this feature one can define easily a hierarchy of objects in a natural way. For example one can define a car that consists of a certain number of doors, wheels, motor and other parts. The motor itself consists of cylinders, pistons, valves, crankshafts and other parts. This definition process can go on and on and on. This feature of keeping the relations in the database is useful for implementing an information system in order to fetch information about any object stored in it.

Object-Oriented Information System

In order to assist control room staff in case of any warnings/failure from the site we decided to configurate and install an OODBS called MATRIX developed by Adra Systems, Inc..The OODBS is a comprehensive designed specifically to manage any type of information in any process environment. It supports the management of documents, the applications that created them, and processes that govern their life cycle.

Matrix operates in a distributed mode within networked system environments of file servers, workstations, and PCs without requiring a dedicated mainframe or minicomputers. Because of its fully distributed architecture, the Matrix System can be used by an entire organization.

Information Management

Access control, integrity, consistency, and *recovery* are fundamental principles for an efficient OODBS.

Access control means that no data is accessible without proper authorization.

Integrity means that each instance of information is unique, with its own history and owner.

Consistency means that people work with data from a variety of sources (e.g. from different applications), but each person has access to the most current information.

Recovery means that all information can be readily stored to the state that existed prior to any failure, whether the result of system failure or human error.

Access Control

The OODBS provides the user with a strong framework for comprehensive access control while giving him a high degree of flexibility. By using the object-oriented database management system access control to the information is assured. This is achieved by using integrated features of **Objectivity / DB** to define rules of ownership for both data and functions. These rules can be defined quickly and flexibly through the visual user interface by establishing various associations between users, data, applications, and processes.

Integrity / Consistency

The integrity of information is of extreme importance. The OODBS assures the integrity and consistency of information in a variety of ways. Each object contains its own unique information, which may be accessed by all people who have the appropriate privileges, yet only one copy of the information exists in the database.

The OODBS cross-checks the object-oriented database to ensure that the information stored within it complies with all defined relationships, process, and format requirements.

Recovery

A data manager must also provide a robust recovery facility. This is not an option, but rather a necessity to insure against data loss; whether the result of system catastrophe, media failure, or undesired user changes.

2. INFORMATION SYSTEM OPERATION

In case any failures the I&C-System generates corresponding warnings comprising device ID and a short failure description. This warning is sent as a telegram via serial interface to the OODBS, starting it automatically (Figure 1).

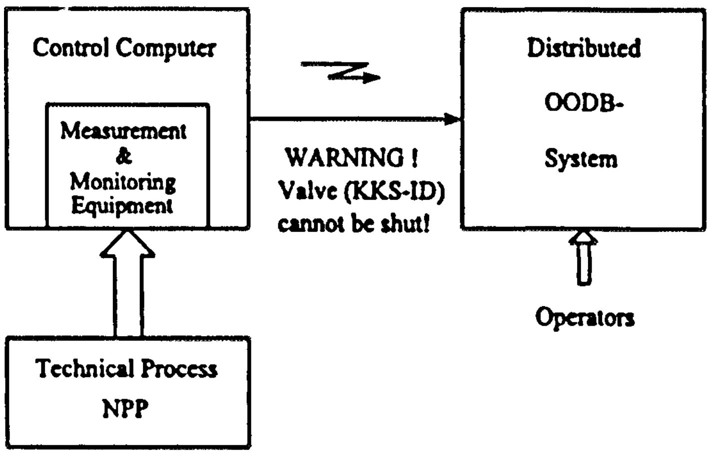

Figure 1: WARNING initiating the OODB-System

Thus, no activity from the operator is necessary e.g. to send any request, like SQL, to the information system. The OODBS starts at once presenting general information due to a certain warning (Figure 2).

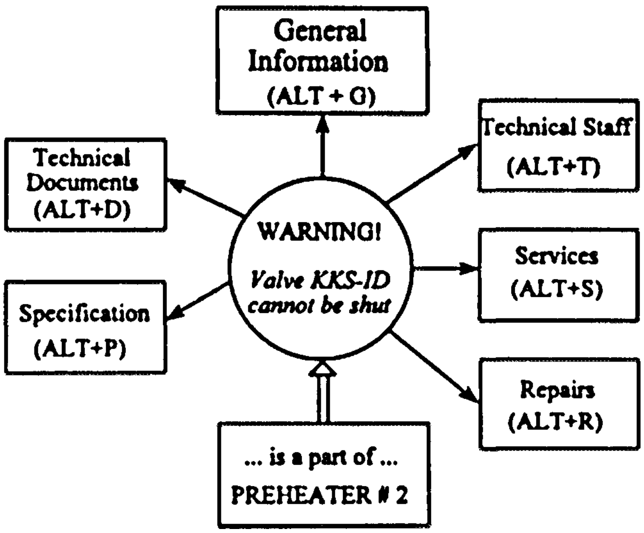

Figure 2: General Information

The warning itself is presented in the center of the screen with connections to available additional information like e.g.

- specification of device
- repairs
- services
- technical staff
- technical documents

due to the reported device. Furthermore, there is presented a link that this reported device is a part of ... (e.g. a part of preheater #2). All symbols for additional information are implemented as *buttons*, so that the operator may choose certain additional information by a simple mouse click. In case of any failures due to mouse device or mouse driver software the operator is able to choose additional information by corresponding keyboard input.

The information system was implemented as a distributed OODBS (Figure 3)

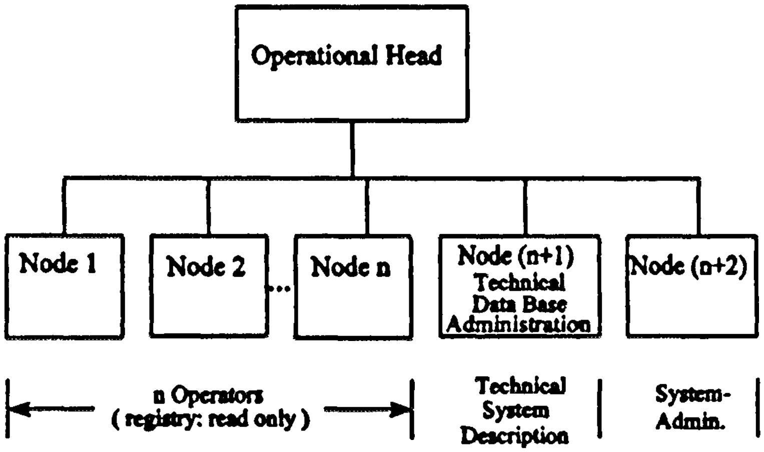

Figure 3: Distributed Object Oriented Database System

If one implements a distributed database system, one or more operators can be provided with reports parallely, e.g. in case of a certain *avalanche of warnings/alarms*. But, because complete information on the plant should be held consistently, operators have access rights for reading only. As shown in figure 3 there are additional nodes: One for complete technical description of the plant that has to be actualized steadily by an authorized engineer and one for software system administration purposes. Both nodes have access rights for reading as well as writing. The operational head of control room staff is provided with an additional node for monitoring purpose.

If the operator clicks on *General Information Button*, he gets additional information at a first level comprising

- ID of device
- device name
- location
- manufacturer
- security level
- date of installation
- maximum value of operation time
- actual value of operation time
- a short description.

In order to avoid that the operator has to change back to first information level, he is provided with a number of *navigation buttons* to change over to further detailled information (Figure 4).

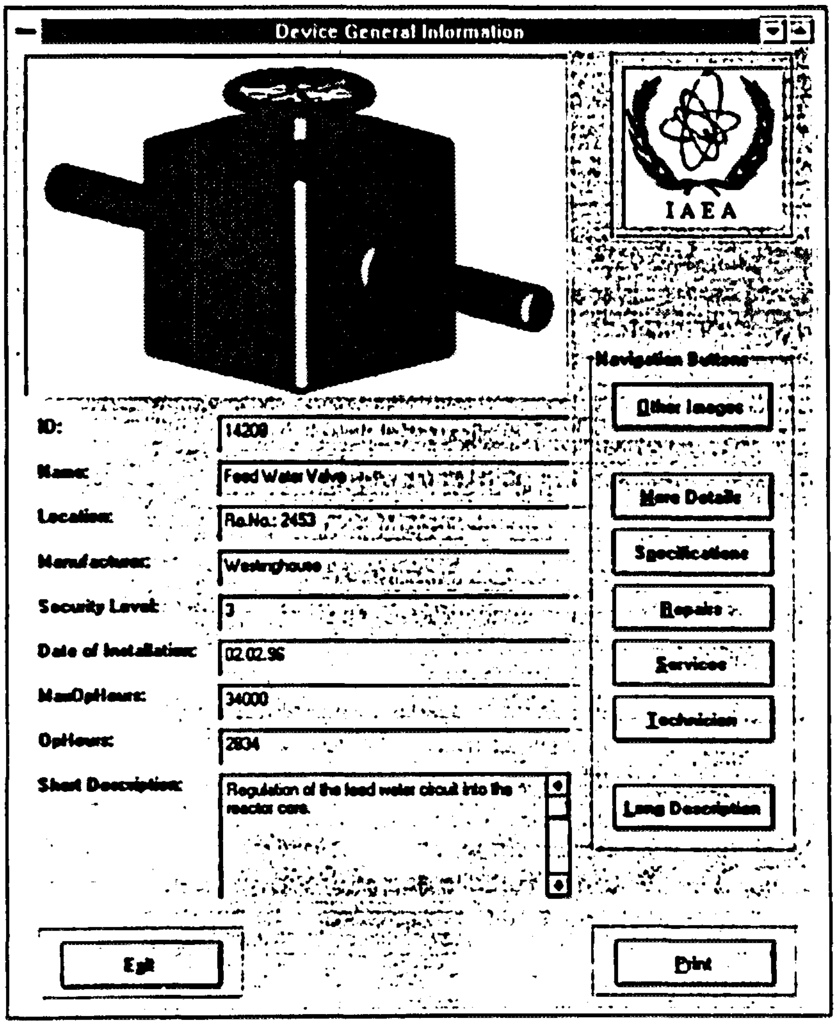

Figure 4: General Information on device

If necessary, the operator can be provided with a detailled device specification (Figure 5).

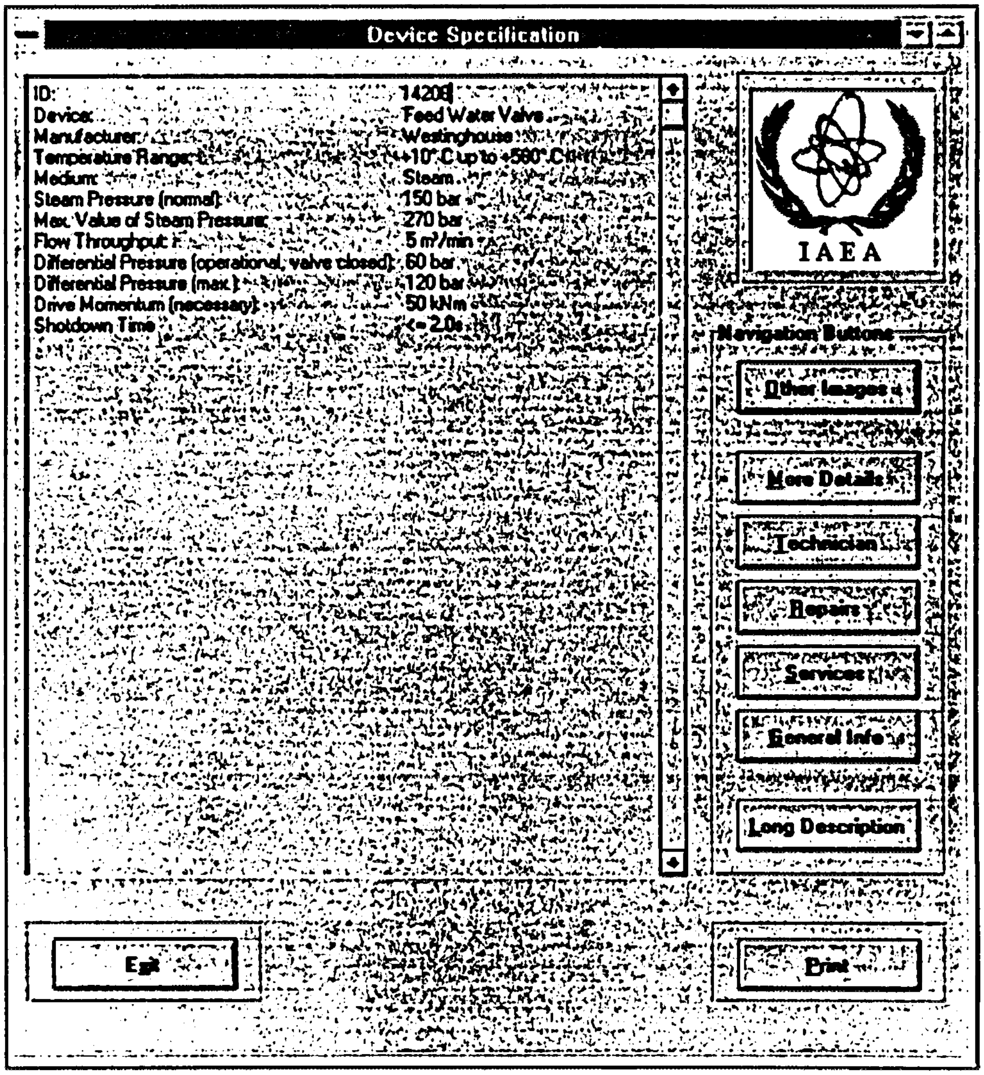

Figure 5: Device Specification

As a historical report the operator is provided with all services done in the past comprising

- service identification
- technician ID
- date of service
- result (as a short description reported by technician)

(Figure 6).

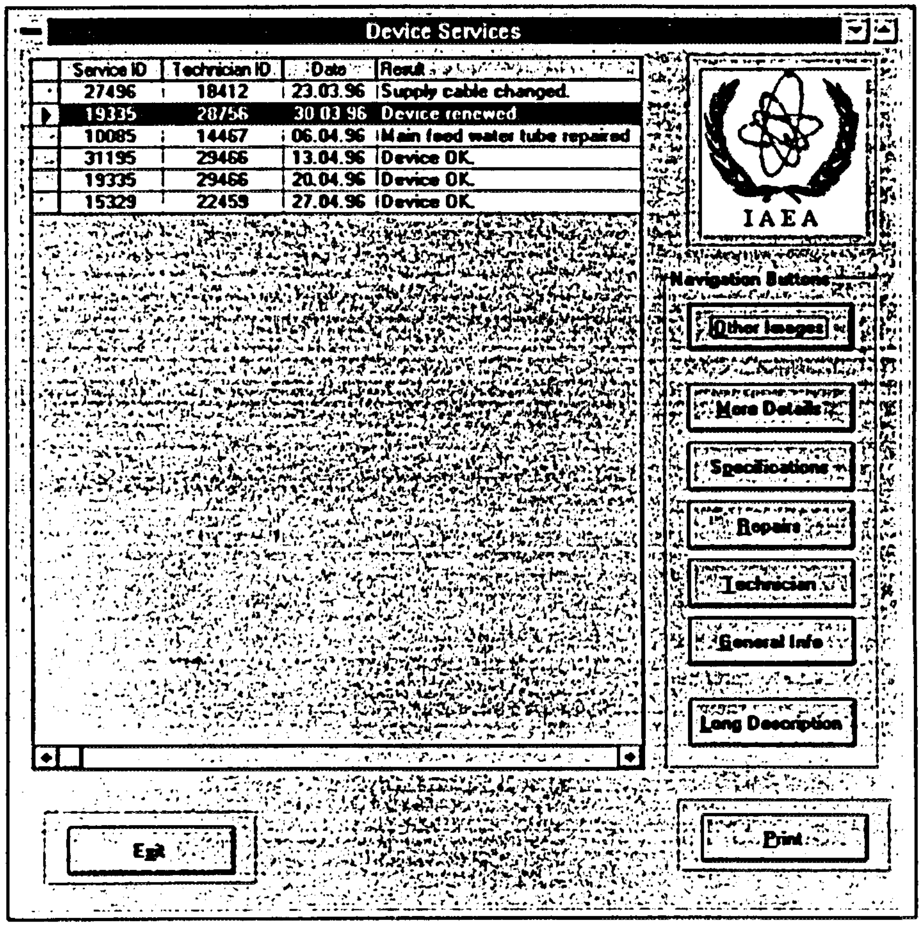

Figure 6: Device Services

The OODBS offers a historical report on repairs of the device done in the past comprising the following information:

- repair order
- technician ID
- date
- result (a short report by technician)

(Figure 7).

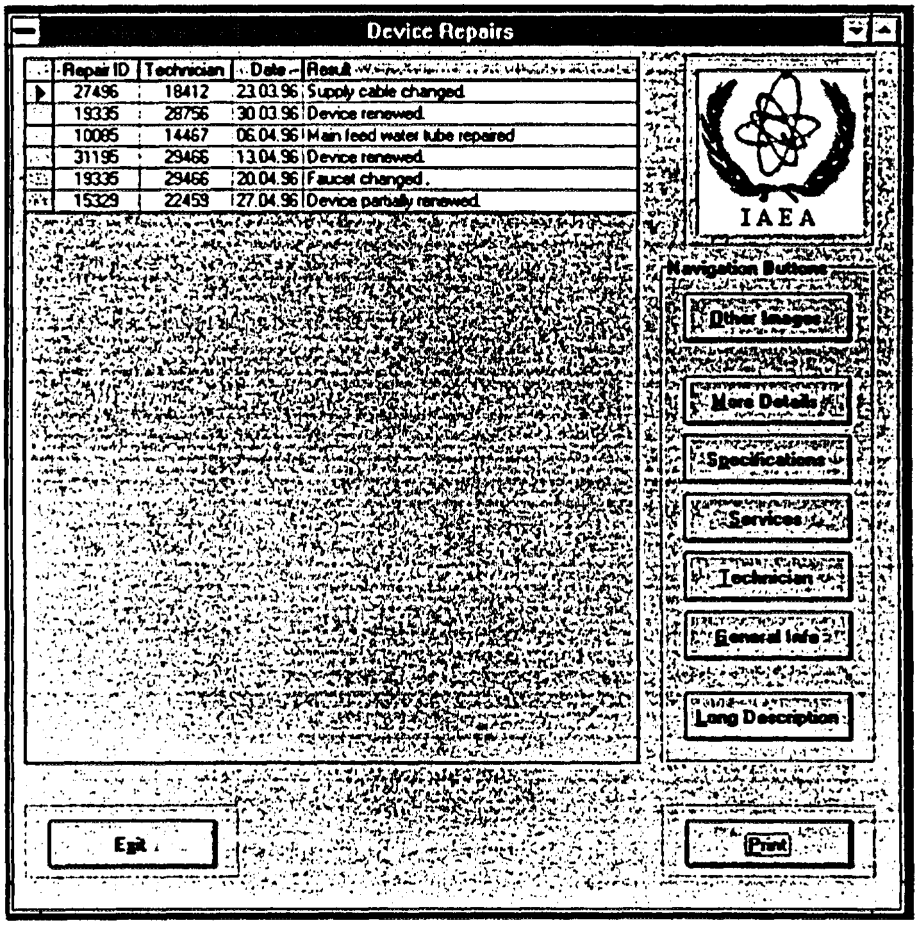

Figure 7: Device Repairs

If the operator needs detailled information on technician staff, he is provided with detailled information:

- technician ID
- name of technician
- security level
- phone number (extension)
- availability (YES or NO)
- qualification
- description of licence for repairs/services
- department (organizational)
- department head (organizational)

(Figure 8).

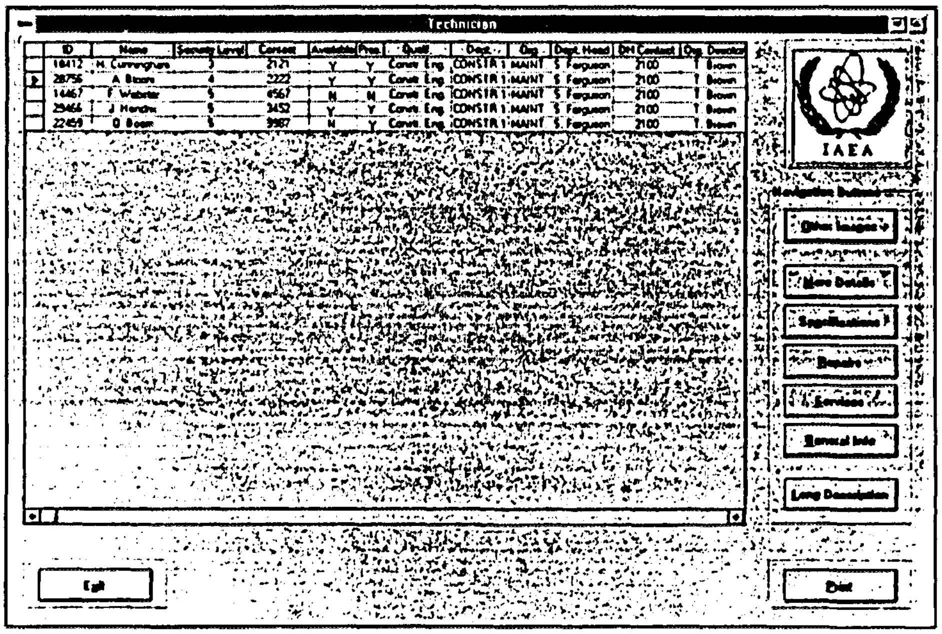

Figure 8: Technician Staff Information

The OODBS contains an additional software interface to personal data acquisition system (PDAS) in order to provide the operator with a *valid* and *actual information*, if a certain technician with wanted licenses is available or not.

If the operator wants to get detailled information on a certain device, he may choose e.g. graphical drafts like CAD documents using CAD-tool CADRA governed by MATRIX automatically (Figure 9).

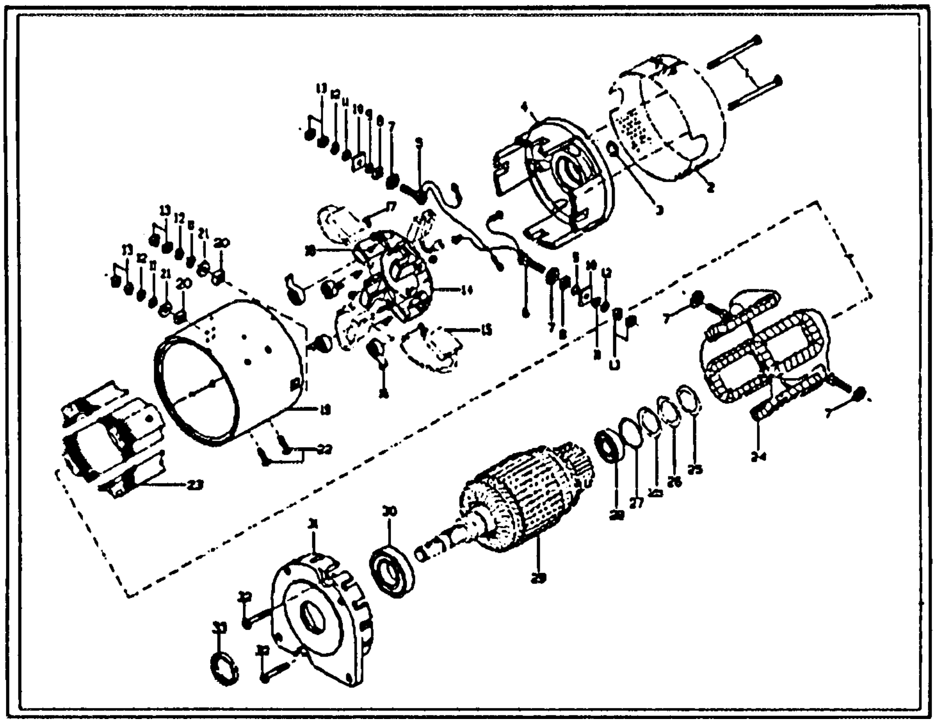

Figure 9: CAD-Document of Device

To ensure that technician has entered to right compartment of NPP to do some repair a telephone communication between operator and technician can be started checking part numbers in the compartment in comparison to a scanned photo presented to the operator by OODBS (Figure 10).

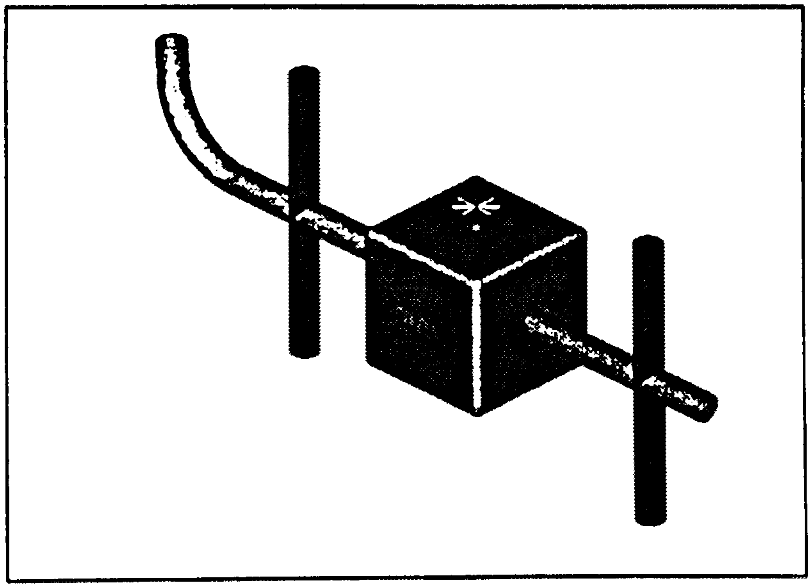

Figure 10: Scanned Photo of Compartment (device & neighbouring devices)

Conclusions

An object-oriented database system was presented. An essential feature of this OODB-System is that it can be installed and configurated as a distributed OODBS. Thus, in a LAN operators can get different information from OODBS in case of alarm avalanches parallely. The OODBS is started automatically by a certain WARNING generated by measurement equipment and presents the operator complete existing information on a failed device, so that he is able to click on any button to get more detailled information. The real-time behaviour of the installed OODBS was found to be excellent. The fundamental advantage of object-oriented-database design is its *expandability.* This OODBS has been developed to assist control room staff under precondition that such an information system will be accepted by control room staff only, if human interface can be handled easily.

Acknowledgements

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NEW TECHNOLOGIES IN NUCLEAR POWER PLANT MONITORING AND DIAGNOSIS

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Abstract

Several representative new technologies being introduced for monitoring and diagnosis in nuclear power plants (NPP) are presented in this paper. In Sec. 2, the Kalman filtering is briefly described and its relevance to conventional time series analysis methods are emphasised. In this respect, its NPP monitoring and fault diagnosis implementations are given and the important features are pointed out. In Sec. 3, the NN technology is briefly described and the scope is focused on the NPP monitoring and fault diagnosis implementations. In Sec. 4, the wavelet technology is briefly described and the utilization of this technology in Nuclear Technology is exemplified. In this respect, also the prospective role of this technology for real-time monitoring and fault diagnosis is revealed.

1 Introduction

Several representative new technologies being introduced for monitoring and diagnosis in nuclear power plants (NPP) are presented in this paper. The new technologies can process information from sensors in the form of fluctuating component, inherently observed in the process signals as well as the gross behaviour of the signals themselves. Due to the developments in the computer technology, new technologies commonly make use of computers for information processing in real-time. Hence, the classical off-line time-series analysis methods are desirably implemented in the form of recursive estimation. An important approach for a unified real-time time-domain sensory information processing for the purpose of monitoring or failure detection and isolation (FDI) is Kalman filtering methodology. By means of this, reliable state estimation and fast response for appropriate preventive and protective actions are realised. Therefore the scope is focused on Kalman filtering based applications concerning FDI. Among the conventional time-domain parametric signal modelling methods are the autoregressive univariate (UAR) and multivariate (MAR) models, single-input-single-output SISO models and multiple-path models (MIMO/MISO). The main improvement by Kalman methodology is due to modelling of measurement errors together with the process noise sources in the form of a stochastic modelling of a dynamic system.

The classical frequency-domain non-parametric monitoring and diagnosis methods are based on fast Fourier transform (FFT) methods which use blockwise global frequency information. A unified approach for conventional time and frequency domain approaches has newly appeared to be multiresolution decomposition and the associated technology is coined as wavelet technology. The other new technology started to be used in NPPs is - artificial intelligence type known as neural networks (NN) which is a generic name for a number of functional structures with a capability of knowledge acquisition. Due to this, it can respond to the environment within the limitations of the knowledge accumulated, independently so that it has very appealing properties with respect to monitoring and diagnostic utilizations in NPPs apart from various other utilizations.

The content of the present paper is as follows. In Sec. 2, the Kalman filtering is briefly described and its relevance to conventional time series analysis methods are emphasised. In this respect, its NPP monitoring and fault diagnosis implementations are given and the important features are pointed out. In Sec. 3, the NN technology is briefly described and the scope is focused on the NPP monitoring and fault diagnosis implementations. The potentialities of this technology are pointed out. In See. 4, the wavelet technology is briefly described and the utilization of this technology in Nuclear Technology is exemplified. In this respect, also the prospective role of this technology for real-time monitoring and fault diagnosis is revealed. Finally, the assessment of the new technologies from reliable and cost effective plant operation viewpoint is discussed.

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2 Real-time Recursive Estimation in Plant Monitoring: Kalman Filtering

By means of Kalman filtering, optimal state estimation for a linear dynamic system is performed. Derivation of Kalman equations are widely available in the literature [1–4]. A brief description of Kalman equations by means of which neural network parameters are computed adaptively, are presented below.

Consider a linear discrete system and assume that modelling technique has produced an adequate description in the form of a linear stochastic system to describe the propagation in time of a state vector $\underline{X}(k)$

$$\underline{X}(k) = \underline{\underline{\phi}}(k, k-1)\underline{X}(k-1) + \underline{\underline{B}}(k)\underline{U}(k) + \underline{\underline{G}}(k)\underline{W}(k) \tag{1}$$

$$\underline{Y}(k) = \underline{\underline{C}}(k)\underline{X}(k) + \underline{V}(k) \tag{2}$$

Here, $\underline{X}(k)$ is a n-vector state process; $\phi(k, k-1)$ the non-singular $n \times n$ system dynamics matrix; $\underline{\underline{B}}(k)$ the $n \times r$ input matrix; $\underline{U}(k)$ the r-vector deterministic input; $\underline{\underline{G}}(k)$ the $n \times p$ noise input matrix; $\underline{W}(k)$ the p-vector white Gaussian noise process; $\underline{Y}(k)$ the m-vector measurement process; and $\underline{\underline{C}}(k)$ the $n \times m$ measurement matrix; $\underline{V}(k)$ the m-vector white Gaussian measurement noise process. The statistics of the noise process $\underline{W}(k)$ and $\underline{V}(k)$ are assumed to be

$$E[\,\underline{W}(k)] = 0 \tag{3}$$

$$E[\,\underline{W}(k_1)\underline{W}(k_2)^T] = \underline{\underline{Q}}\delta_{k_1 k_2} \tag{4}$$

$$E[\,\underline{V}(k)] = 0 \tag{5}$$

$$E[\,\underline{V}(k_1)\underline{V}(k_2)^T] = \underline{\underline{R}}\delta_{k_1 k_2} \tag{6}$$

where δ is the Kronecker delta, $\underline{\underline{Q}}(k)$ and $\underline{\underline{R}}(k)$ are $p \times p$ symmetric positive-semidefinite and positive-definite matrices, respectively. The system noise $\underline{W}(k)$ includes the effect of variability in the natural system as well as model structure errors. The measurement noise $\underline{V}(k)$ represents the uncertainty associated with the measurement process. The initial condition $\underline{X}(0)$ is assumed to be Gaussian with statistics:

$$E[\,\underline{X}(0)] = \hat{\underline{X}}(0) \tag{7}$$

$$E\{[\,\underline{X}(0) - \hat{\underline{X}}(0)]\, E[\,\underline{X}(0) - \hat{\underline{X}}(0)]^T\} = \underline{\underline{P}}(0) \tag{8}$$

where $\underline{\underline{P}}(0)$ is the $n \times n$ symmetric positive-definite matrix.

The estimate of the system state $\underline{X}(k)$ can be obtained by the help of the information provided by the system model and the measurements $\underline{Y}(k)$ obtained from the actual system. For the solution of this filtering problem the Bayesian approach is used and the conditional probability density of the state $\underline{X}(k)$, conditioned on the entire history of the measurements, is identified. Once this density is explicitly described, an optimal estimate of the state $\underline{X}(k)$ can be defined. Under the assumption of the model given above, the conditional density is Gaussian and it is completely characterized by its mean and covariance matrix. Hence, the estimate of $\underline{X}(k)$ based on the conditional density will results in the same estimated $\hat{\underline{X}}(k)$ and the same covariance matrix of the estimation error $\underline{\underline{P}}(k)$. The optimal state estimate is propagated from measurement time $k-1$ to measurement time k by the equations

$$\hat{\underline{X}}(k|k-1) = \underline{\underline{\phi}}(k, k-1)\underline{X}(k-1|k-1) + \underline{\underline{B}}(k)\underline{U}(k) \tag{9}$$

$$\begin{aligned}\underline{\underline{P}}(k|k-1) \quad = \quad & \underline{\underline{\phi}}(k, k-1)\underline{\underline{P}}(k-1|k-1)\underline{\underline{\phi}}(k, k-1)^T + \\ & \underline{\underline{G}}(k)\underline{\underline{Q}}(k)\underline{\underline{G}}(k)^T \end{aligned} \tag{10}$$

At measurement time k, the measurement $\underline{Y}(k)$ becomes available. The estimate is updated by the equations:

$$\hat{\underline{X}}(k|k-1) = \hat{\underline{X}}(k|k-1) + \underline{\underline{K}}(k) \cdot [\underline{Y}(k) - \underline{\underline{C}}(k)\hat{\underline{X}}(k|k-1)] \tag{11}$$

$$\underline{\underline{P}}(k|k) = \underline{\underline{P}}(k|k-1) - \underline{\underline{K}}(k)\underline{\underline{C}}(k)\underline{\underline{P}}(k|k-1) \tag{12}$$

where

$$\underline{\underline{K}}(k) = \underline{\underline{P}}(k|k-1)\underline{\underline{C}}(k)^T \cdot [\underline{\underline{C}}(k)\underline{\underline{P}}(k|k-1)\underline{\underline{C}}(k)^T + \underline{\underline{R}}(k)]^{-1} \tag{13}$$

is the filter gain. In Eq. 11 $[\underline{Y}(k) - \underline{\underline{C}}(k)\hat{\underline{X}}(k|k-1)]$ is called the *innovation*. Extended versions of the Kalman algorithm can be applied to non-linear dynamic systems by linearizing the system around the current estimate of the parameters and this is described elsewhere [5].

Kalman filter can be viewed as an information filter in the form of inverse covariance matrix [6] and it is directly related to the Bayesian probabilistic information. The recursive estimation scheme provides step by step updated probabilistic information accumulation. The covariance matrix provides the updated information on errors of the state estimates. This information can be used in variety of ways for NPP monitoring and failure detection. In this respect, computation of the Mahallanobis distance is one of the essential methods [7]. Powerful class of detection schemes for system and instrument failures perform statistical tests on the innovations sequence of a Kalman filter [8–12] where the filter innovations are the difference between the actual plant measurements and the measurement estimates. Fig. 1 describes the incore sensor surveillance application [8] by Kalman filter system modeling where artificial sensor anomaly is virtually cannot be perceived at the estimated data which is approximately equal to the variation of the measurent data since the sensor noise is rather low. However, innovation sequence clearly expose the anomaly.

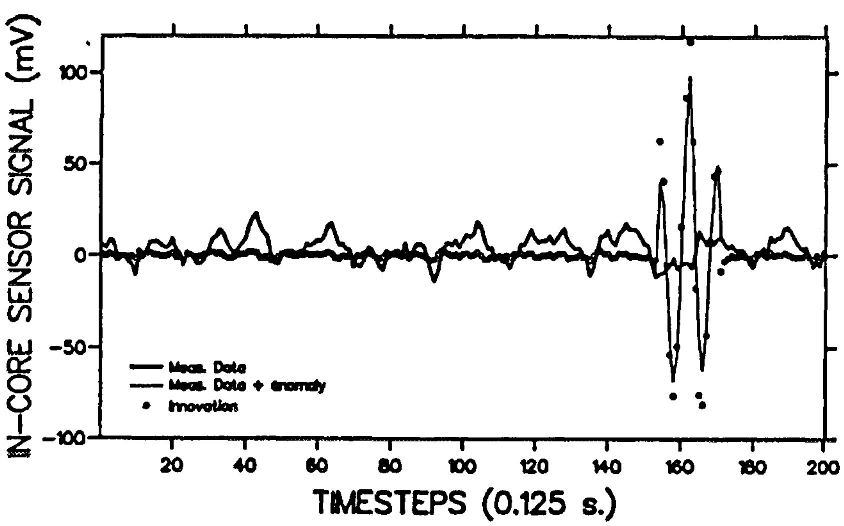

Fig. 1: *In-Core sensor measured signal used for failure detection. Kalman filter input is provided with the measured signal which is formed by averaging signals from the redundant sensors [8].*

3 NN Technology in NPP Monitoring and Diagnosis

Neural network (NN) is a data processing system consisting of a number of simple, highly interconnected processing elements in an input/output architecture. A neural network is generally structured with a set of N elementary processing units arranged in several layers. At the first neuronal layer which is called first hidden layer, each neuron receives at its inputs the outputs coming from external information sources and at the subsequent layers which are called subsequent hidden layers, each neuron receives at its inputs the outputs of the preceding layer. In particular, the last neuronal layer is called output layer. The very first layer where no neuron exists is the input layer which contains the inputs or the external information. The hidden layers receives the information provided by the immediate lower level neurons and send the processed information directly to the upper layer. The output layer delivers the final processed information for use in the intended application.

There are several different kinds of learning commonly used with neural networks. Perhaps the most common is supervised learning in which a stimulus is presented at the input layer of the network and the output from the output layer is sent to a system that compares it with a desired output and then uses a corrective or learning algorithm to convert the error formed by the difference into an adjustment of the weighting coefficients that control the inputs to the various processing elements. In a typical situation, the initial weighting functions are set randomly and then subjected to incremental changes determined by the learning algorithm. When an input is again applied to the input layer, it produces an output which is again compared with the desired output to produce a second error signal. This iterative process continues until the output of the of the neural network is virtually equal to the desired output. At that point the network is said to be 'trained'. Further, through the various learning algorithms, the network gradually configures itself to achieve the desired input/output relationship called 'mapping'.

The counterpart of the supervised learning is the unsupervised learning algorithm where only the input stimuli are applied to the input layer of the network. The network then organizes itself internally so that each hidden processing element responds strongly to a different set of input stimuli. These sets of input stimuli represent clusters in the input space.

The neural network may be designed so as to classify an input pattern as one of several predefined type of fault states of a power plant for easy recognition of such a state in critical situations. These applications have demonstrated high performance. A relevant application for accident management is described before [12]. Another desirable feature of neural networks is their ability to respond in real-time to the changing system state descriptions provided by continuous sensor input. For a NPP where many sensors are used the real-time response is a challenge to both human operators and expert systems. Neural networks have the ability to recognize patterns, even the information making up these patterns is noisy or incomplete. This makes adaptive neural networks ideally suited for fault diagnosis, control and risk evaluation in NPP environments.

The integration of neural networks with an expert system provides neural network utilization with a substantial potentiality for fault diagnosis. In this case the monitoring system has the functionality of being an operating support system as the decisions made are based on the NPP knowledge base, which is at the disposal of expert system. A real-time application of such system is at the operating Borssele nuclear power plant [13, see Fig. 2] and described before [14]. The application is schematically illustrated in Fig. 3. and Fig. 4. There are a number of favourable reported neural network applications in nuclear industry and they are described in literature [15–25].

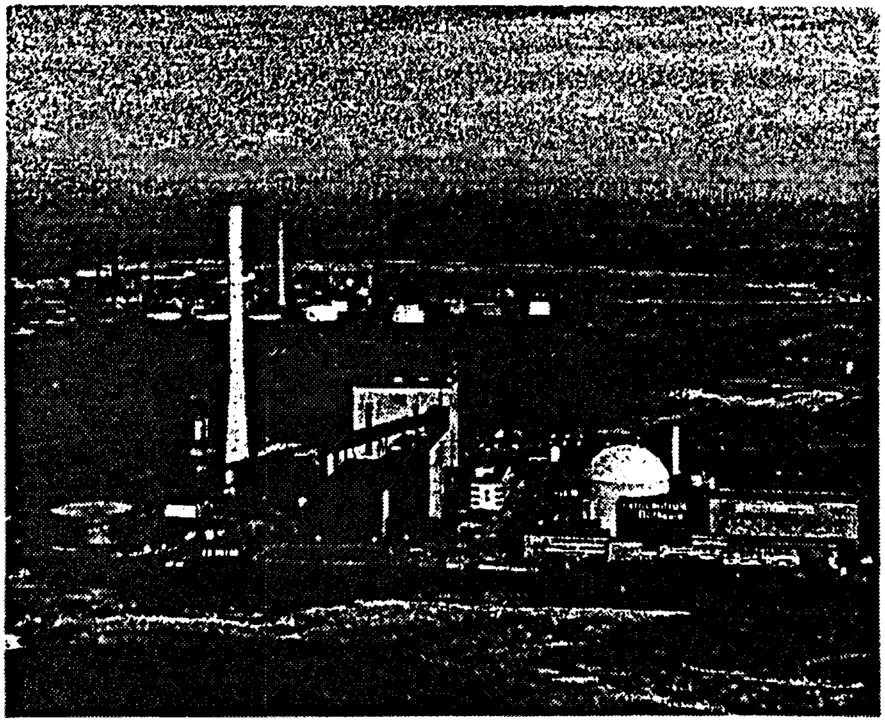

Fig. 2: *The Borssele power plants: conventional (left), nuclear (right).*

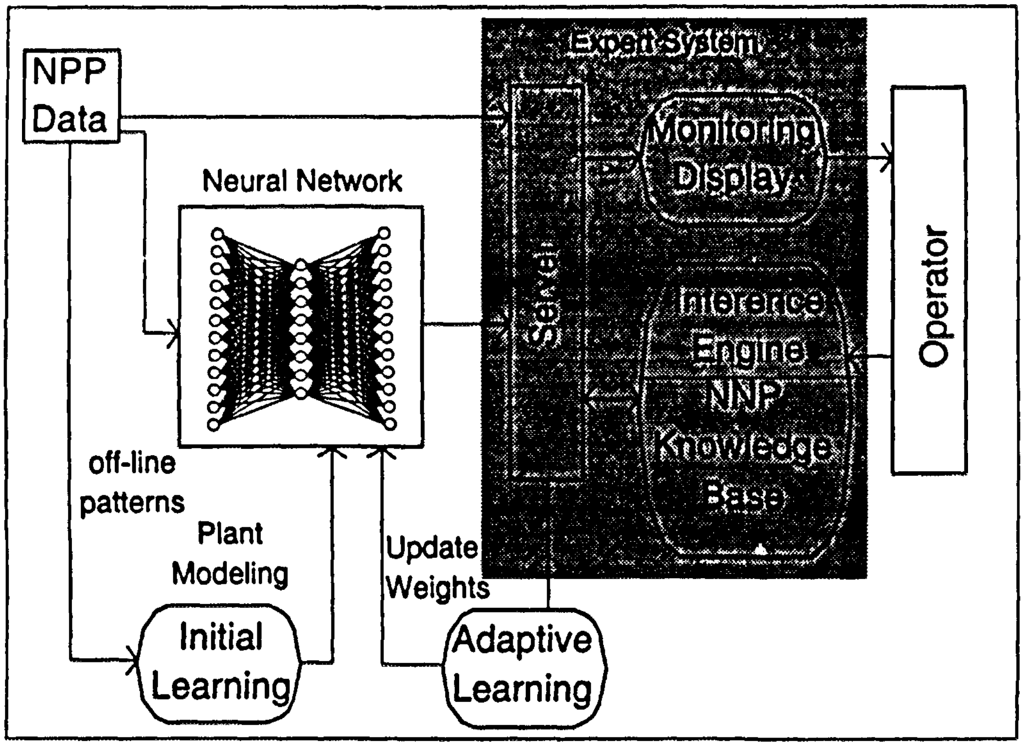

Fig. 3: *Diagram of Hybrid AI System [14]*

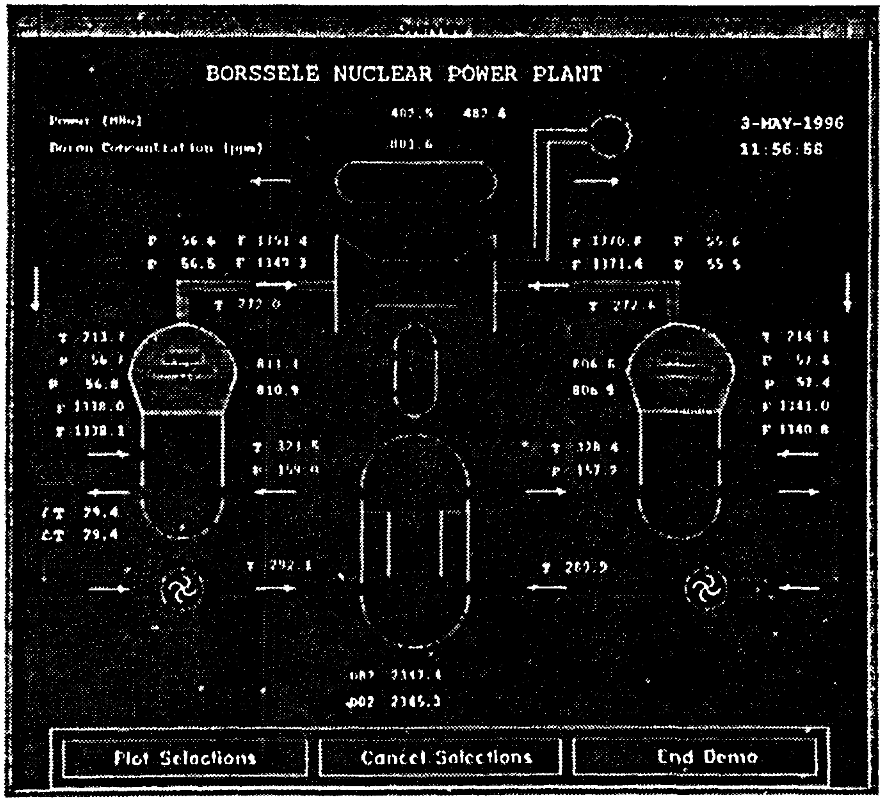

Fig. 4: *Monitoring display by real-time neural network; Measured and NN estimated (light) values.*

4 Wavelet Technology

Traditionally, the reactor noise is represented by means of its spectrum or Fourier transform in frequency domain and by means of time series modeling in time-domain. However both methods have their limitations as well as their merits. Especially global information on the frequency domain do not reveal any time relevance to a frequency domain phenomenon. On the other hand, time series analysis does not yield any frequency domain relevance before a frequency domain transformation. i.e. $z = exp(j\omega)$, is performed, z bezing the z-transform variable and ω represents frequency. With respect these limitations, in sensory information processing in NPP these limitations are of particular nondesirable issues. Referring to this, a relatively recent development appeared in applied mathematics as a new methodology the industrial applications of which lead to a new technology coined as wavelet technology. It deals with the operation, known as wavelet transform which is a tool that cuts up data or functions into different frequency components, and then studies each component with a resolution matched to its scale. In the signal analysis framework, the wavelet transform of signal evolving in time depends on two variables: scale which is related to frequency and translation which is related to time. Hence, wavelets provide a tool for time-frequency localization. In contrast with convential approach alternatively, choosing a time-frequency approach for studying of non-stationary signals the emphasis being mainly on time variations concerning spectral characteristics, in the wavelet approach rather non-stationary signal is considered as a superposition of a number of elementary components which are more or less localized, In this class of approach, the choice of frequency as auxiliary variable is not required and is replaced by that of 'scale'. Such a process is referred to as multiresolution signal decomposition. Wavelet transform finds applications in many diverse areas. Potential utilization in nuclear power plant monitoring and sensory information processing have been recently proposed [26–27]. A short introduction of wavelet transforms is given below to convey the ideas about its functionality and outstanding potentialilitics in nuclear industry.

Given a time-varying signal $f(t)$, wavelet transform provides coefficients, called 'wavelet coefficients', which are resulted from the inner products of the signal and a family of 'wavelets'. Referring to the continuous wavelet transform, the wavelet corresponding to a scale 'a' and time location 'b' is

$$\Psi_{a,b}(t) = \frac{1}{\sqrt{|a|}}\Psi\left(\frac{t-b}{a}\right) \tag{14}$$

where $\Psi_{a,b}(t)$ is the wavelet which is an element of the space $\mathbf{L}^2$. Functions, f, in this space must satisfy

$$\int |f(x)|^2\,dx < \infty \tag{15}$$

The wavelet is subject to the following additional constraints

1.
$$\int \Psi(x)\,dx = 0 \tag{16}$$

2. Both Ψ and its Fourier transforms $\hat{\Psi}$ must be window functions, that is, they must have a well defined center and radius so that they are localized in both the time and frequency domains within the limits imposed by the Uncertainty Principle [3]. Hence wavelet can be thought of as a bandpass function so that it must decay rapidly and also exhibit some degree of oscillation. Having pointed out these concepts, we can define the Integral Wavelet Transform (IWT)

$$(W_\Psi f)_{(b,a)} = |a|^{-1/2}\int f(t)\,\overline{\Psi_{a,b}\left(\frac{t-b}{a}\right)}\,dt \tag{17}$$

where $a, b \in \mathbf{R}$ and $f \in \mathbf{L}^2$ and the overbar denotes complex conjugation. Since Ψ is by definition localisable in both time and frequency scale, the IWT is also localised and gives us information in both domains within the bounds of the Uncertainty Principle.

There are several ways of discretizing time-scale parameters (b, a) so that each one yields a different type of wavelet transform. Considering the continuous wavelet transforms, wavelet series coefficients are sample IWT coefficients. To ensure computational efficiency time remain continuous but time (localisation)-(frequency) scale parameter (b, a) are sampled on a 'dyadic' grid in the time-scale plane of the form

$$a = 2^j \quad , \quad b = k\,2^j \quad , \quad j, k, \in \mathbf{Z} \tag{18}$$

so that the wavelets take the form

$$\Psi_{j,k}(t) = 2^{j/2}\Psi(2^j t - k) \quad , \quad j, k, \in \mathbf{Z} \tag{19}$$

which results in

$$(W_\Psi f)(k2^j, 2^j) = \langle f, \Psi_{j,k} \rangle = d_k^j \tag{20}$$

Above $<, >$ indicates the inner product defined by $\langle f, g \rangle = \int f(x)\overline{g(x)}\,dx$ and the coefficients d_k^j are called wavelet coefficients. For orthogonal wavelets for which

$$\langle \Psi_{j,k}, \Psi_{l,p} \rangle = \delta_{jl}\delta_{kp} \qquad \text{for all } j, k, l, p, \mathbf{Z} \tag{21}$$

every $f \in \mathbf{L}^2$ has a unique series expansion:

$$f(t) = \sum_{j,k} \langle f, \Psi_{j,k} \rangle \, \Psi_{j,k}(t) \tag{22}$$

This is the inverse transform formula by means of which we may recover our original function from sampling. In other words, the formula relates the transform coefficients to the original function that it is called perfect reconstruction. The discrete wavelet transform (DWT) is a wavelet transform for discrete-time signal where both time and scale parameters are discrete. As far as the structure of computations is concerned, the DWT is seemingly the same as an octave-band filter bank.

A multiresolution signal decomposition [24] by wavelet transform is shown in Figs. 5 and 6. Fig. 5 indicates steamflow variations representing the transient for two steam generator steamflows in a power plant. Fig. 6 shows the signal decomposition by wavelet transform for steamflow 2 at nominal power (location I in Fig. 5).

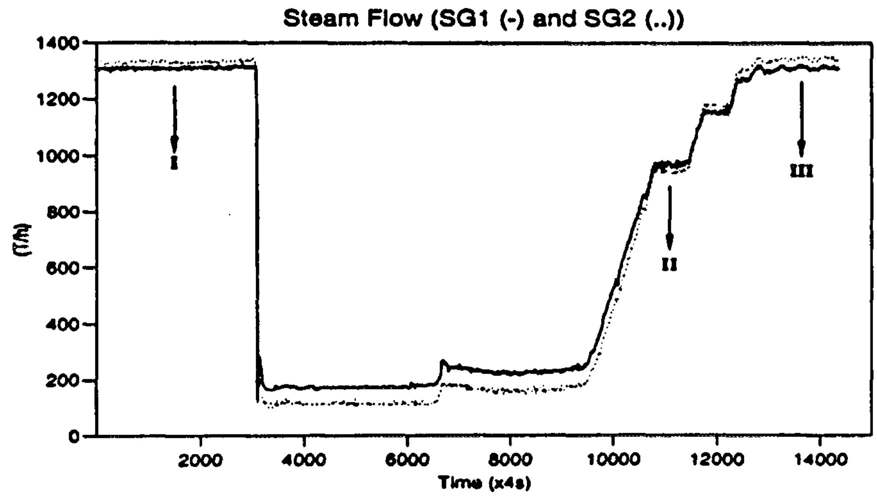

Fig. 5: *Steamflow variations representing the transient for two steam generator steamflows; locations are indicated as I, II, and III for wavelet analysis.*

5 Discussion and conclusion

The importance of the Kalman filtering in a dynamic system modeling like NPP, can be seen as follows. A dynamic system whose state variables are the estimates of the state variables of another system is called an observer of the latter system. This is

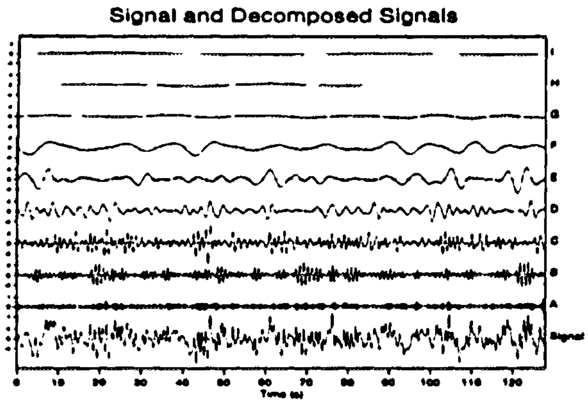

Fig. 6: *Power spectral density (PSD) corresponding to the signal decomposition by wavelet transform for steamflow 1 at nominal power for region I.*

Signal: AC signal; 8 s/s

A: decomposed signal for	4.	to 8.	Hz
B: decomposed signal for	2.	to 4.	Hz
C: decomposed signal for	1.	to 2.	Hz
D: decomposed signal for	0.5	to 1.0	Hz
E: decomposed signal for	0.25	to 0.5	Hz
F: decomposed signal for	0.125	to 0.25	Hz
G: decomposed signal for	0.0625	to 0.125	Hz
H: decomposed signal for	0.03125	to 0.0625	Hz
I : decomposed signal for	0.015625	to 0.03125	Hz

introduced into linear system theory by D. Luenberger [28, 29]. However, Kalman filter has the structure of a linear observer, so in a sense a linear observer may be regarded as a suboptimum Kalman filter. Alternatively, a Kalman filter may be regarded as an optimum observer. The optimality of recursive Kalman filter estimates with the equivalent recursive information update form provides a modern approach to time series analysis for real-time information processing.

Among the artificial intelligence techniques, neural networks have been proposed to provide support for NPP operators. The applications are spread over a wide range of support areas including plant parameter estimation [30, 31], NPP transient event classification [20], dynamic system identification [32], thermal performance evaluation of power plants [25, 33] which are among many other applications. The reported high performances of these applications are very encouraging. Although in these applications, the reliability of neural network estimations are not yet explicitly addressed, at the present stage, neural networks can pragmatically be considered as rather robust and reliable auxiliary supporting tool for NPP operations. However, the appropriate performance measures for robustness and reliability should be defined and related issues should be thoroughly addressed before they replace the conventional methods.

Wavelet technology has already found firm implementations in other (non-nuclear) areas. Among these the area of communication can be articulated. However, the multiresolution signal decomposition in real-time implies that the signal is splitted up into several orthogonal components so that each component signal can be treated effectively for enhanced information processing in NNP operation. The enhancement is achieved by means of the decomposition process called mathematical zooming. Therefore, wavelet technology surely will gain gravity in nuclear industry too while the wavelet-based signal analysis tools are commercially made available and/or the relatively difficult mathematical foundations of wavelet is satisfactorily understood by the application engineer.

6 Acknowledgement

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GENERAL KNOWLEDGE STRUCTURE FOR DIAGNOSIS

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ABSTRACT

At the OECD Halden Reactor Project work has been going on for several years in the field of automatic fault diagnosis for nuclear power plants. Continuing this work, studies are now carried out to combine different diagnostic systems within the same framework. The goal is to establish a general knowledge structure for diagnosis applied to a NPP process. Such a consistent and generic storage of knowledge will lighten the task of combining different diagnosis techniques. An integration like this is expected to increase the robustness and widen the scope of the diagnosis. Further, verification of system reliability and on-line explanations of hypotheses can be helped. Last but not least there is a potential in reuse of both specific and generic knowledge. The general knowledge framework is also a prerequisite for a successful integration of computerised operator support systems within the process supervision and control complex. Consistency, verification and reuse are keywords also in this respect. Systems that should be considered for integration are; automatic control, computerised operator procedures, alarm - and alarm filtering, signal validation, diagnosis and condition based maintenance.

This paper presents three prototype diagnosis systems developed at the OECD Halden Reactor Project. A software arrangement for process simulation with these three systems attached in parallel is briefly described. The central part of this setup is a 'blackboard' system to be used for representing shared knowledge. Examples of such knowledge representations are included in the paper. The conclusions so far in this line of work are only tentative. The studies of existing methodologies for diagnosis, however, show a potential for several generalisations to be made in knowledge representation and use.

1. INTRODUCTION

The work on plant surveillance systems including diagnosis has a long history at the OECD Halden Reactor Project (HRP). A variety of diagnosis techniques and applications have been implemented since the late eighties. In the past few years the work on diagnosis has been aimed at combining different techniques and methods. There are two major objectives of this work:

- Improved performance and reliability of automatic diagnosis applied to NPP processes.
- More efficient design process for knowledge-based operator support systems, and thereby an increased employment of these systems in the NPP industry.

Core tasks in diagnosis include a search for and presentation of valid hypotheses with fault explanations. Solutions to such tasks have been demonstrated successfully in the previous studies. There is, however, still room for improvements and tuning of the methods. The design process has been addressed, but no final methodology has been chosen. The experience from system developments in the project demonstrates the need for guidelines, or a toolbox, for diagnosis system design. Also different aspects of system integration have been studied but still more work is to be done before a concept can be endorsed.

At the moment the direction pursued is an in-depth investigation of the basis for diagnosis. Diagnosis is bounded by accessible relevant knowledge. Therefore an effort to improve diagnosis could be made by coordinating a search for and a representation of knowledge. In diagnosis of rotating machinery elicitation of operational data is thought to be the major bottle-neck [1]. In other domains the dominant problems of fault diagnosis are related to representation and use of knowledge. Recognising these problems it has been decided to direct the work towards a general representation of knowledge utilised in diagnosis. This raises two questions; what knowledge is used in diagnosis and how to make a general representation.

There are two aspects for which such a knowledge storage is thought to be of use. First it is meant to serve the *diagnosis process* as such, and its application to the plant in question. A consistent and generic storage of knowledge will greatly assist in combining different diagnosis techniques. This will increase the robustness and widen the scope of the diagnosis. Further, verification of system reliability and on-line verification of hypotheses can be facilitated. Last but not least there is a big potential in reuse of both specific and generic knowledge. The second aspect is *integration of computerised operator support systems* within the process supervision and control complex. A general knowledge framework is a prerequisite for a successful combination of the design tasks, like extraction of domain knowledge, and merging the run-time systems. Consistency, verification and reuse are keywords also in this respect.

The next part of this paper gives an overview of three different diagnosis systems. Two different kinds of knowledge represented in these systems are identified. Section 3 presents a simulation set-up including the three diagnosis systems. A central module of this simulation setup is meant to hold some of the knowledge found in the diagnosis systems. The tool and methodology used in making this module is under development in a bilateral project at HRP [2]. Examples of how this tool can be used for knowledge representation are given. The intended outcome of simulations with the set-up is also related. Conclusions and future work constitute the last part of the paper.

2. PROTOTYPE DIAGNOSIS SYSTEMS

Several prototype diagnosis systems have been developed at the OECD Halden Reactor Project. Methods and techniques range from rule-based, model-based, Goal-Tree Success-Tree, to artificial neural networks and fuzzy logic. The developments have followed the historical evolution of methods in the field of artificial intelligence. Often the work has been performed in co-operations with other centres of research. Three diagnosis systems are presented here. Examples of knowledge used in these three systems to diagnose a specific failure are also included. The three systems are studied to find what knowledge is stored in their structures.

2.1 DISKET

DISKET was developed in the mid-eighties, in cooperation with Japan Atomic Research Institute (JAERI) [3], and has been thoroughly tested in the HAlden Man-Machine LABoratory (HAMMLAB) [4]. This is a *rule-based* system containing knowledge of transient behaviour to expand the diagnosis beyond the traditional steady-state process application of rule-based systems.

Fault detection is made by comparing measurements to alarm limits. These alarm limits are given by four qualitative values or by percentages. The hypotheses are organised by physical location in an hierarchical structure where the lower levels pinpoint the origin of failure. In this way isolation and identification are combined. To move through this tree there are rules of stronger and stronger fault explanations. The strength of each explanation is presented explicitly by probability factors. A diagnosis is made whenever the confirmed explanations of a hypothesis have a combined probability factor exceeding a certain limit.

Originally DISKET was coded in FORTRAN but a limited G2-implementation [5] has been made and is used in the current research. In the G2 knowledge base all faults are marked with global identifiers. These are also applied to the two other diagnosis systems presented in this paper. This G2 implementation of DISKET is meant to recognise nine hardware and controller faults in the High Pressure Preheater (HPP) unit described in section 2.4. One of these hardware faults is *heat exchanger 1 (HX1) tube leakage*. Water from the main water flow is leaking into the heat exchanger tank. A DISKET diagnosis of this fault is made from the following sequence of observations:

1 One or more of the heat exchanger tank level measurements of the HPP-unit are registered

with a value above the safety limit.

2 One or more of the heat exchanger tank outlet valves are more than 95% open.
OR
One or more of the heat exchanger tank level measurements of the HPP-unit are registered with a value above the safety limit.

3 The level measurement of HX1 is registered with a value above the safety limit, *and* the tank outlet valve of HX1 is more than 95% open.
OR
The level measurement of HX1 is registered with a value above the safety limit within 60 seconds after the outlet valve of HX1 is more than 95% open.

2.2 EFD/DD

Early Fault Detection (EFD) and Detailed Diagnosis (DD) were developed in consecutive order, as respectively *fault detection* and *fault identification* systems. In combination the two modules perform *model-based* fault diagnosis. The modules, and several applications were made at the OECD Halden Reactor Project during the years 1985-1993 [6] [7].

EFD is based on a partitioning of the target process with a mathematical model of each subprocess. Fault detection is performed by a continuous matching of measurements and predictions relating to each subprocess. Discrepancies between the predictions and the observed behaviour are reduced to a qualitative range of three values. The predictions are made with redundant observations, enabling verification of some sensors. Fault hypotheses are defined in the DD knowledge base. The hypotheses are grouped according to the subsystems modelled in EFD. Fault identification is made in two steps, first the discrepancies found by EFD are matched with symptom patterns stored in DD. The next step use parameter gradient information to select a most probable hypothesis based on the fault candidates identified by the proceeding stage.

The EFD module is programmed in FORTRAN, receiving input from the NOkia Research Simulator (NORS). Corresponding applications of DD have been implemented on a Symbolics LISP workstation and in G2. The G2 version of DD include 35 different fault hypotheses for hardware, controller and sensor failures of the HPP section illustrated in section 2.4. The fault model related to diagnosis of *HX1 tube leakage* in this system include the following observations:

1 The measured outlet flow from the tank of HX1 is not consistent with the flow calculated from heat and mass balances based on other measurements.

2 The measured tank level of HX1 is rising, and the tank outlet valve of HX1 is opening.

2.3 MOAS II

Another *model-based* diagnosis system was developed at the OECD Halden Reactor Project with the MOAS methodology derived at Maryland University by Modarres and co-workers [8]. The diagnosis system development with this method involves a functional analysis, building Goal-Tree Success-Trees (GTST) to identify key surveillance parameters in the process. Knowledge represented in the form of causal graphs is also used in the system design, illustrating plausible causes of observed behaviour. The application created at the OECD Halden Reactor Project was named MOAS II [9].

In MOAS II a small set of measurements are used to detect faults and trigger diagnosis. These measurement values are verified by equations relating redundant sensor information. If any measurements fail to be verified the fault is assumed to be caused by a failing sensor. Isolation and identification of these faults are made by systematically applying mathematical relations interrelating the set of involved measurements. All other faults are identified by first checking weak explanations derived from cause-effect graphs pointing to hypothesis candidates. Secondly strong explanations are used to weed out impossible candidates.

G2 was used for the original implementation, allowing graphical presentation of the diagnosis inference. The present knowledge base contains 48 hypotheses of hardware, sensor and controller failures for the HPP section. However some of the hypotheses are only present in a diagnosis as one of two possible fault explanations. Again we present the inference leading to a diagnosis of *HX1 tube leakage*:

1 One or more of the heat exchanger tank level measurements of the HPP-unit are registered with a value above the safety limit.
2 The main measurements of the HPP-unit verify each other.
3 The tank level of HX1 is above the safety limit, or both the tank levels of HX1 and HX2 are above the safety limit, or all the tank levels of HX1, HX2 and HX3 are above the safety limit.
4 The measurements of the main water flow into HX3 and out of HX1 are not the same, and the calculated mass balances of the HX1 tank are not consistent.

2.4 Demonstration domain

The High Pressure Preheater (HPP) process unit has been chosen to demonstrate the principles and methods of diagnosis. This unit has been used extensively in previous demonstrations and applications developed at the Halden Reactor Project and was selected for the present study because of this. The process is simulated by the NOkia Research Simulator (NORS) installed in HAMMLAB. The NORS process is almost identical to the IVO nuclear power plant (PWR, 500MW), Loviisa, Finland.

The HPPs increase the overall efficiency of the NPP by heating the water before it enters the steam generator in the secondary loop. The unit consists of three heat exchangers coupled in series. The main water flow is supplied at a high pressure from the feed water tanks. Steam is retrieved from bleeding points of the steam turbines, while the hot water comes from a tank. Figure 1 sketch the input-output layout and main components of the HPP section.

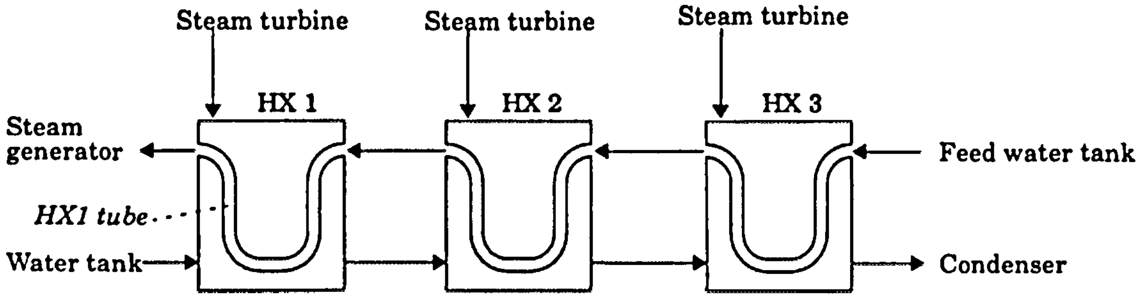

Figure 1. High Pressure Preheater

Some possible fault situations in this heat exchanger network are; leakage of main water into heat exchanger tank, non-functioning control valves, failing sensors and leakages from tubes and tanks to the environment.

2.5 Knowledge used in diagnosis systems

Two types of knowledge can be said to exist in the diagnosis systems described above. Most apparent of the two is the process knowledge like power plant data. A major part of the knowledge used in making a diagnosis is of this kind. This knowledge can be described in terms of the observable parameters, process behaviour, topology and faults related to the application domain of the diagnosis system. The other important type of knowledge in the diagnosis systems is the knowledge of reasoning on how to make a diagnosis. This knowledge is used when making new diagnosis systems, verifying diagnoses and mapping capabilities, strengths and weaknesses of diagnostic methods. This knowledge is used for applying the process knowledge in diagnosis. Examples of diagnostic knowledge are knowledge of backward and forward chaining methods, the detection task, reliability of diagnoses from a diagnosis system, scope of the diagnosis system, and knowledge of methods for identifying key surveillance parameters used in the detection operation.

3. COMPILING KNOWLEDGE FOR DIAGNOSIS

Abilities and distinctions of several diagnosis systems are to be collected and compared to each other. This is done in order to learn more about the knowledge stored in each particular system. A software setup for simulations has been made to facilitate such a knowledge acquisition. The setup include concurrent operation of the three systems DISKET, EFD/DD and MOAS II described in section 2. The diagnoses resulting from the simulations are reported to the central module of the setup. This module is made in a 'blackboard' system referred to as *the BlackBoard*. Creating this application of the BlackBoard is the first step in generating a general knowledge framework for diagnosis. The BlackBoard tool is under construction in a separate project at the HRP [2]. In addition to the connections to the three diagnosis systems the BlackBoard is also linked to a program performing an analysis of the reported diagnoses. The software programs and their interfaces are illustrated in Figure 2.

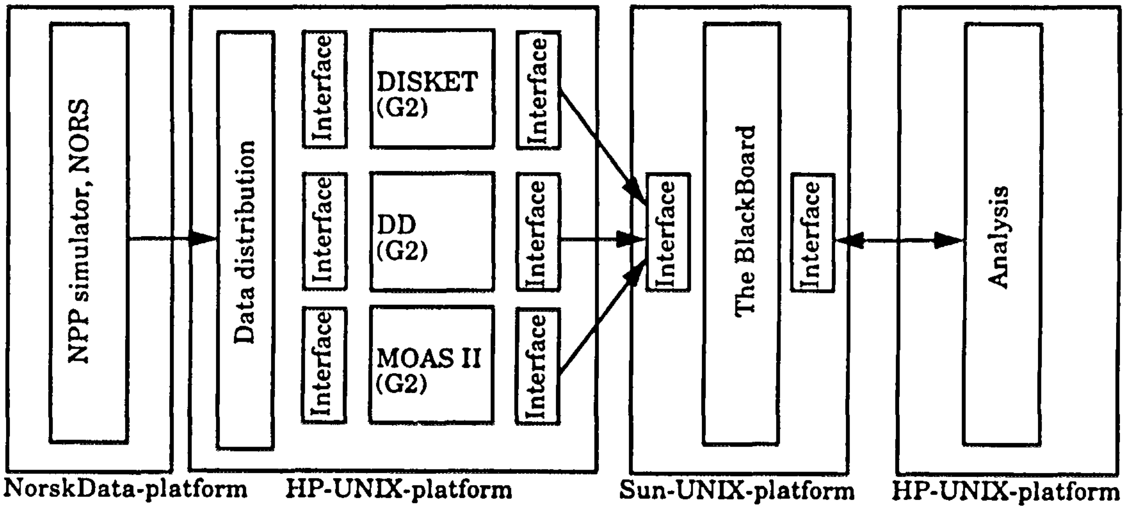

Figure 2. Setup for parallel diagnoses

First we will give a description and examples of how to represent knowledge on the BlackBoard. Then features of the simulation setup regarding compilation of knowledge is related.

3.1 The BlackBoard

The purpose of the BlackBoard is to coordinate and communicate knowledge coming from diverse knowledge sources. A knowledge source could be almost any form of code describing a system or procedure. Typically the knowledge sources work together to solve a problem. This requires the BlackBoard to represent knowledge in an acceptable format, and to transfer knowledge to and from a multitude of agents. The analogy to a blackboard used at school is good. Envision a group of people gathered around the blackboard to solve a problem. They are allowed only to communicate by writing or erasing on the blackboard.

Representation of knowledge on the BlackBoard is facilitated by objects. Object classes, object instances, object attributes and object relations are to be made for the domain in question. Lists, originating objects and special relations are used to keep track of the elements on the BlackBoard. Communication with external entities is enabled by functions working on the structure of objects. Another important feature of the BlackBoard is the ability to restrict access to knowledge. Depending on the access level of a knowledge source certain parts of the knowledge domain are hidden or revealed.

How to represent knowledge on the BlackBoard is to a large extent based on the domain itself and what the knowledge is to be used for. There are indeed very few rules or limitations, allowing the BlackBoard to be applied to a broad range of system domains. This flexibility can on the other hand lead to lack of conformity. To secure some consistency the BlackBoard is delivered with a set of defined relations. One of these is the 'is-a' relation, made to connect object classes and instances. However, the BlackBoard does not define semantics associated with relations [10]. As a consequence it is difficult to create good ontologies for the domains on the BlackBoard. Here ontology means *specification of a conceptualization*, a definition applied in the context of knowledge sharing [11].

What knowledge to store on the BlackBoard is partly a question of what knowledge should be shared between multiple agents and what is better left to be presented in the knowledge sources. Other issues affecting what knowledge to represent on the BlackBoard concern the original knowledge format and the software interfaces of the BlackBoard.

Technically the BlackBoard exists as a C++ program. Libraries contain definitions and functions to create domains for the BlackBoard and connections to other knowledge sources. Parallel Virtual Machine (PVM) software is used for creating the server-client architecture [12]. A graphical interface based on Gain Momentum is being developed [13].

3.2 Process knowledge on the BlackBoard

Concepts and particular process knowledge of a NPP are needed in diagnosis systems for the plant. Much of the data are common to more systems and should therefore be presented on the BlackBoard. This would also allow diagnosis systems of different methods to share the knowledge of a specific NPP. There are already a multitude of ontologies and representational techniques made for process knowledge of the NPP domain. However, few of these offer simple application, verification and reuse in computerised operator support systems.

An example of how topological knowledge can be stored on the BlackBoard is given in Figure 3. This knowledge is of course again connected to other kinds of knowledge in the diagnosis systems. In Figure 3 there is both system independent (generic) knowledge, presented in the form of classes, and system specific knowledge, as objects, from the NPP domain. System dependent topological knowledge, like the class instances and relations in Figure 3, is used in isolating the location of faults.

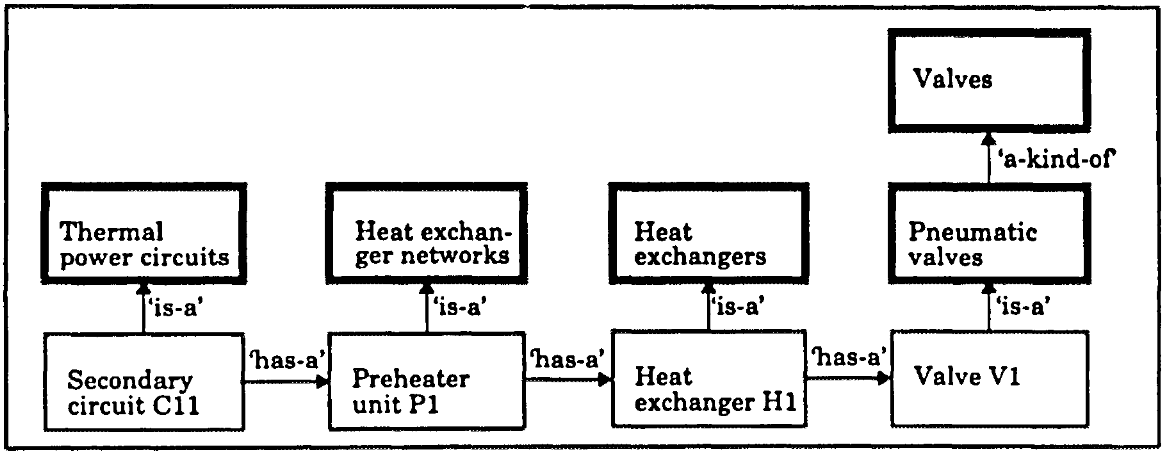

Figure 3. Example of generic and specific topological knowledge

A second example on how to represent process knowledge on the BlackBoard displays elements of process behaviour. There are many ways to represent such knowledge. Figure 4 illustrates an approach with *function* objects. Other commonly used representations present behaviour as *events* or *states*. In portraying knowledge of behaviour it is pertinent to show the casual relations between the functions, events or states. These relations illustrate the connections creating the global operation.

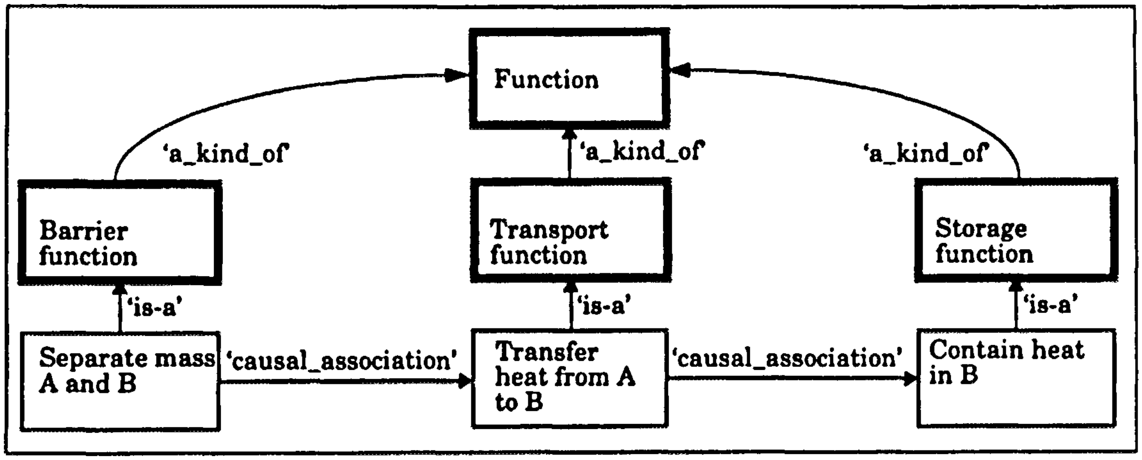

Figure 4. Behavioural knowledge by functions

3.3 Knowledge of diagnostic reasoning on the BlackBoard

In the AI field diagnosis methods are divided into two broad classes the *model-based* and *association-based* methods. Such a classification is for example made in the CommonKADS Library [14], where the two methods are called *consistency-based* and *association-based*. Inspired by the KADS models Figure 5 visualize some ideas for presenting knowledge of these methods on the BlackBoard. However, any detailed frameworks encompassing all the aspects of what we call diagnostic knowledge have not yet been found, and it is therefore hard to make examples of representations on the BlackBoard. The non-physical nature of diagnostic knowledge is also making it less intuitive to think of appropriate classes and objects to be placed on the BlackBoard to illustrate this knowledge.

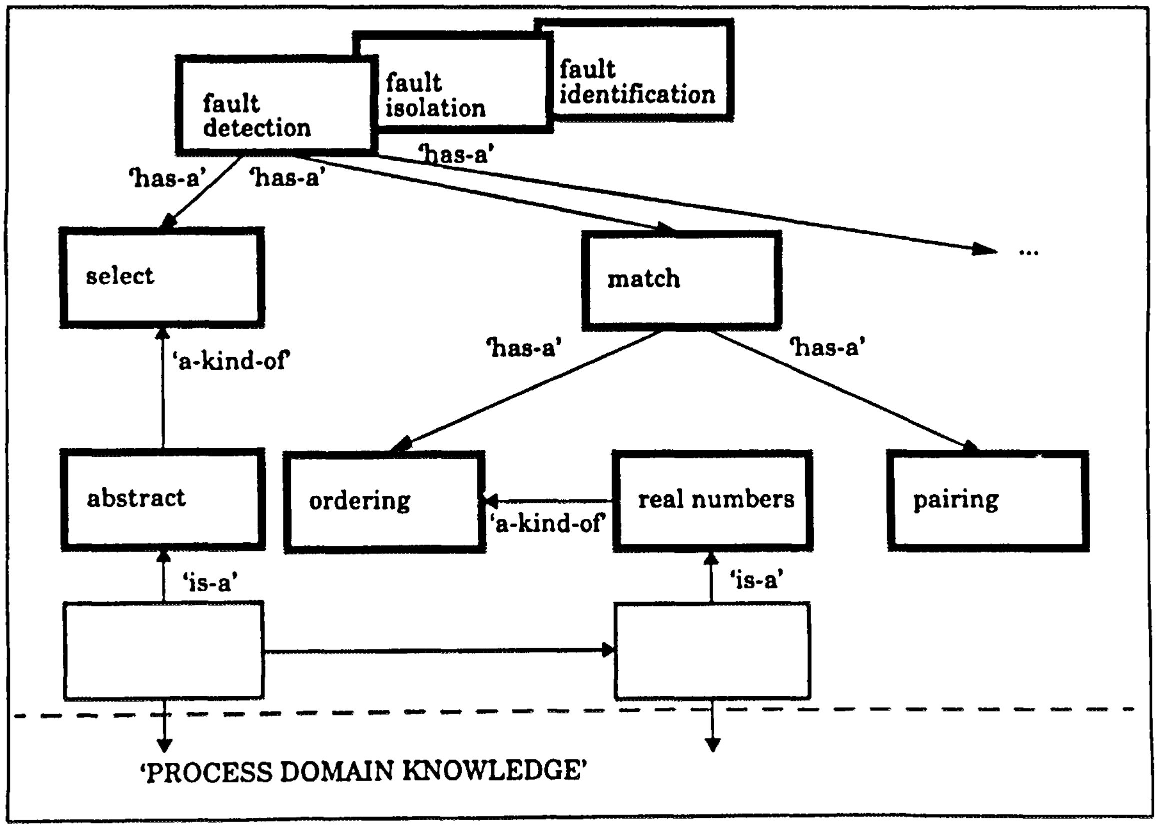

Figure 5. Concepts used in association- and model-based diagnosis

3.4 Simulation-based learning

A simple architecture for knowledge used in diagnosis has been implemented on the BlackBoard, see Figure 6. The main intention of this structure is to allow compilation of knowledge from diagnosis systems, but it is also thought to be the starting point for a framework of knowledge used in diagnosis. Both process knowledge, like the hypotheses related to the process in question, and diagnostic knowledge represented by for instance the 'Hypotheses' class are shown in Figure 6.

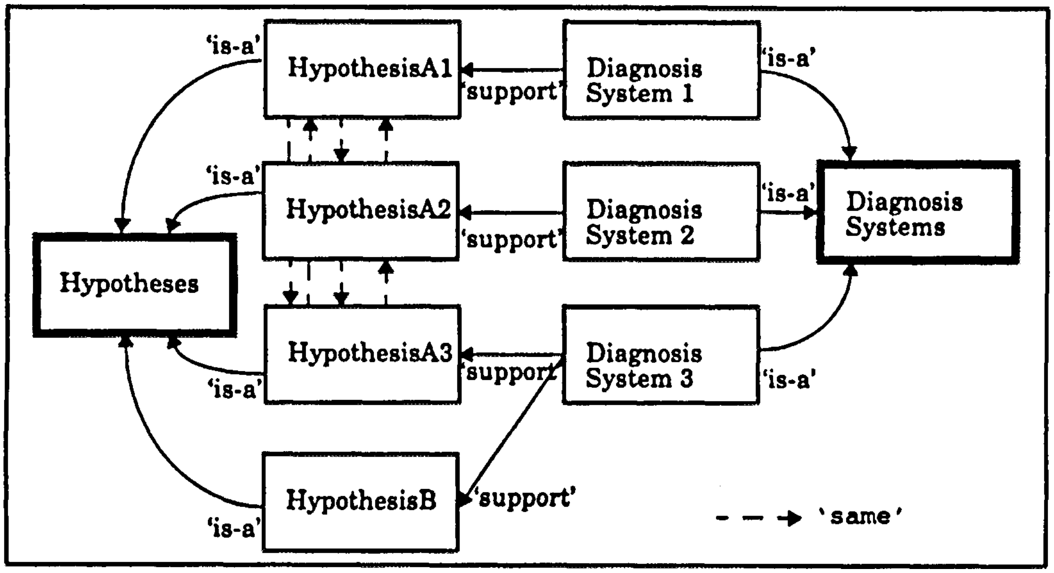

Figure 6. Basic BlackBoard domain model for diagnosis

The intended compilation of knowledge require an analysis of scenario results collected on the BlackBoard. The actual simulation scenarios have not yet been made or run with this setup, but an analysis module is developed in order to assist in evaluating the diagnoses reported to the BlackBoard. This analysis module is connected to the BlackBoard as a knowledge source with two-ways communication as shown in Figure 2. Only a simple form of reasoning is currently performed by this knowledge source. The diagnoses reported to the BlackBoard are compared in order to find whether all the diagnosis systems report the same fault and at what point in time the faults are diagnosed. Extensions are necessary both in the BlackBoard domain (Figure 6) and this analysis module to investigate other features of the diagnosis systems in the simulation setup.

The knowledge attained from the simulations is of course limited to the knowledge stored in the connected diagnosis systems. Hopefully it will be possible to acquire both process and diagnostic knowledge through the simulations. The current setup is expected to tell us what hypotheses are the same in the different diagnosis systems, what hypotheses overlap and maybe which ones are contradictory. Simple knowledge of the scope and reliability of the particular systems can perhaps also be retrieved by investigating the results of many simulation scenarios.

4. CONCLUSIONS

Three prototype diagnosis systems are described by their applications of knowledge and examples of knowledge related to a particular fault. These examples indicate a similarity in the actual knowledge used by the three different systems. A better comparison and possible integration of the systems or their methods require a more thorough analysis of the systems. Such an analysis is thought to be facilitated by simulation. A simulation setup has been made and is presented with the three diagnosis systems attached to it.

The central module of the simulation setup is made with a 'blackboard' system named *the BlackBoard*. The description of the BlackBoard and the examples of representations of knowledge for diagnosis illustrate how the BlackBoard can be utilised in creating a general knowledge structure for diagnosis. Recalling our intentions this structure is expected to assist in improving both the design process of diagnosis systems and the diagnosis process itself by supporting reuse, integration and verification.

Future work include running simulations with the setup of diagnosis systems. This is hoped to give both new insight in the particular diagnosis systems and diagnosis system knowledge in general. New prototype diagnosis systems can be connected to the setup for testing and investigation. The lessons learned from the simulations will also assist in expanding the knowledge structure on the BlackBoard. Extensions to this structure are to be made both for process and diagnostic knowledge.

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ADVANCED SOFTWARE TOOLS FOR DIGITAL LOOSE PART MONITORING SYSTEMS

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ABSTRACT

The paper describes two software modules as analysis tools for digital loose part monitoring systems. The first module is called acoustic module which utilises the multi-media features of modern personal computers to replay the digital stored short-time bursts with sufficient length and in good quality. This is possible due to the so-called puzzle technique developed at ISTec. The second module is called classification module which calculates advanced burst parameters and classifies the acoustic events in pre-defined classes with the help of an artificial multi-layer perceptron neural network trained with the back propagation algorithm.

1 INTRODUCTION

Loose part monitoring systems (LPMS) based on structure-borne sound analysis are installed in all nuclear power plants (NPPs) with light water reactors in Germany. The systems work on-line and monitor continuously possible detached or loosened internal or foreign parts in the reactor coolant system. In recent years more and more utilities have replaced or are planning to replace old analogue systems with modern digital systems. These computer-based systems allow more flexible handling of acoustic burst events and in principal also more intelligent burst judgement to reduce false alarms on-line or to carry out burst posterior processing and trending after alarm.

The Institut für Sicherheitstechnologie (ISTec) GmbH has extensive experience with analogue and digital LPMSs [1] and performed successful research work on intelligent on-line burst processing methods [2]. In frame of programs of the Federal Ministry for Environment, Nature Conservation and Nuclear Safety (BMU) for further development of surveillance methods of NPPs, ISTec developed two software modules for computer aided burst judgement. They are implemented as add-ons (MS Windows 3.1 dynamic link libraries DLLs) for industrial LPMSs e.g. the Siemens/KWU LPMS KÜS'95, stage 2.

2 CONTEXT OF WORK

Modern digital loose part monitoring systems in nuclear power plants detect structure-borne acoustic events (bursts) caused by impacting loose parts, sliding and rolling actions, cavitation- or other flow instability induced noise. Parallel to the alarm setting into the control room the detected events are usually digitised with a 50 or 100 kHz sampling rate per channel (A/D resolution: 12 or 16 bit) and stored on hard disc. The registered time window is typically 50 to 100 milliseconds [3], [4]. Figure 1 shows an example of an 8 channel acoustic event detected by the LPMS KÜS95.

The detailed evaluation of the acoustic events requires normally extensive know how and analysis efforts, although standard software analysis tools for burst processing are available in a modern LPMS. They include algorithms e.g. for RMS-, FFT- or inverse FFT-transforms, for digital filtering, amplitude-, occurrence time- and delay time statistics, rough and fine localisation of event source, etc. Other helpful tools are trend analysis together with recorded process signals and cyclic background measurements and analysis etc. The tendency is also going to deliver tools for energy and mass estimation of loose parts in the future. With the help of these tools a trained operator in the plant or an external expert can carry out the burst evaluation interactively.

On the other side, an operator has normaly to care of more than one system in the plant and also other daily tasks. It is extremly helpful to him in practice, if the system can give an idea about the rough location of the signal origin like "reactor pressure vessel bottom" and about the signal type like "metallic impact" or "flow induced noise" with less interactive effort. Only the interesting or unsure cases have to be investigated more detailed. General speaking, one can perform the burst judgement in a subjective and/or objective way:

- In the subjective way the expert makes the decision according to his visual (through the form comparison of time signals) or acoustic impression (through hearing of the relevant channels). The success rate is personal dependant. It works only in off-line modus.

- In the objective way some feature values from the measured data are determined and the decision is based on pattern recognition techniques. It works also on-line and the success rate depends on the quality of selected feature values and on the power of the applied pattern recognition algorithms.

The acoustic module supports the subjective way and the classification module supports the objective way of decision making.

3 ACOUSTIC MODULE

Despite of the dramatic development in data processing technology human ear remains a unbeatable instrument for the perception and detection of acoustic events. Until now an acoustic replay of the registered digitised short time burst signals isn't available, although it has been found already with the old analogue systems that the audio replay is a helpful way of burst evaluation. Some digital LPMS-systems have analogue tape recorders (even with expensive solid-state delay unit for catching the first hit) build in, but they are cost and maintenance intensive and not user friendly.

The technical difficulty is that a direct replay of the stored data with a duration of 50 to 100 ms by a simple D/A conversion makes less sense, because human ear needs some time (>300 ms) to perceive the acoustic events. The so-called puzzle technique developed at ISTec solves the problem in a sufficient way [5]: Almost all digital LPMSs record the burst signal with a pretrigger part (typically 20 to 30% of the time window), which is normally a background signal of the channel and free of impact content. The idea is to extract the channel background noise information and to generate a longer (typically 2 sec.) acoustic signal in which the burst is embedded. This artificial signal is stored in MS-Windows WAV-format and can then be easily replayed by the PC sound card to the headphone/loudspeaker. The main steps are given in figure 2.

The puzzle and replay procedure can be done of course not only for a single burst event but also for an ensemble of sequential or arbitrarily selected bursts of one selecteed channel or all channels. Figure 3 shows a hard copy of the user dialogue for the ensemble replay. The user can easily go forward or backward through the selected bursts, and repeating from beginning etc. Of course it is also possible to perform frequency transformation and loudness control in a digital way which is planned in a later version of the module.

Test results in ISTec acoustic lab demonstrate clear differences in the sound impression for different burst types such as metallic impacts, flow induced noise or elektrical/thermal disturbance signals.

4 CLASSIFICATION MODULE

Besides of the subjective burst evaluation e.g. by means of the acoustic module or through visual time signal judgement, it is also possible to carry out the automatic burst classification. With the positive experience gained during a PWR steam generator monitoring application [2] and a benchmark application for the process monitoring [6], the ISTec classification module is based on an artificial neural network with five input nodes (x1 to x5), two hidden layers with five nodes each, and two output nodes (y1 and y2), figure 4.

Five parameters which characterise the burst form adequately, are determined automatically: the local maximum time (=Tlm), the global maximum time (=Tam), the normalised area, the intensity ratio and the fine structure [7]. They are used as inputs of the neural network and the output value y1 determines the class value. y2 is a sensor identification value. Each event is classified as one of the five possible classes (or an unknown class): Elektrical/Thermal disturbance signal, Burst signal, Flow induced noise, Calibration signal and Background signal. Figure 5 show the user dialogue for the single event classification and figure 6 the user dialogue for the burst ensemble classification.

Test results in ISTec acoustic lab achieved a correct classification rate of ca. 90%. The super user in the plant can extend the user training set and retrain the network for adaptation of the diagnostic capability to special signal paths in his plant without any change of the software. Figure 7 shows the training dialogue for the super user.

In this way the digital stored signal patterns can be classified into the pre-defined classes automatically.

5 CONCLUSIONS

Two software modules for operator support are described. They are useful for modern digital loose parts monitoring systems. The acoustic module makes acoustic replay of digital stored short time bursts possible. The classification module calculates the feature values of unseen acoustic events and classifies them with the help of a trained artificial neural network in pre-defined classes automatically. Both modules are implemented using MS-Visual C++ programming language as MS-Windows 3.1-DLLs. They can be called by the LPMS KÜS'95-Shell directly. It is also possible to adapt them to other digital LPMS if neccessary.

The two modules as an optional part of the KÜS'95 will be installed in the Russian plant Balakovo and also (at least) in one German plant this year.

6 ACKNOWLEDGEMENT

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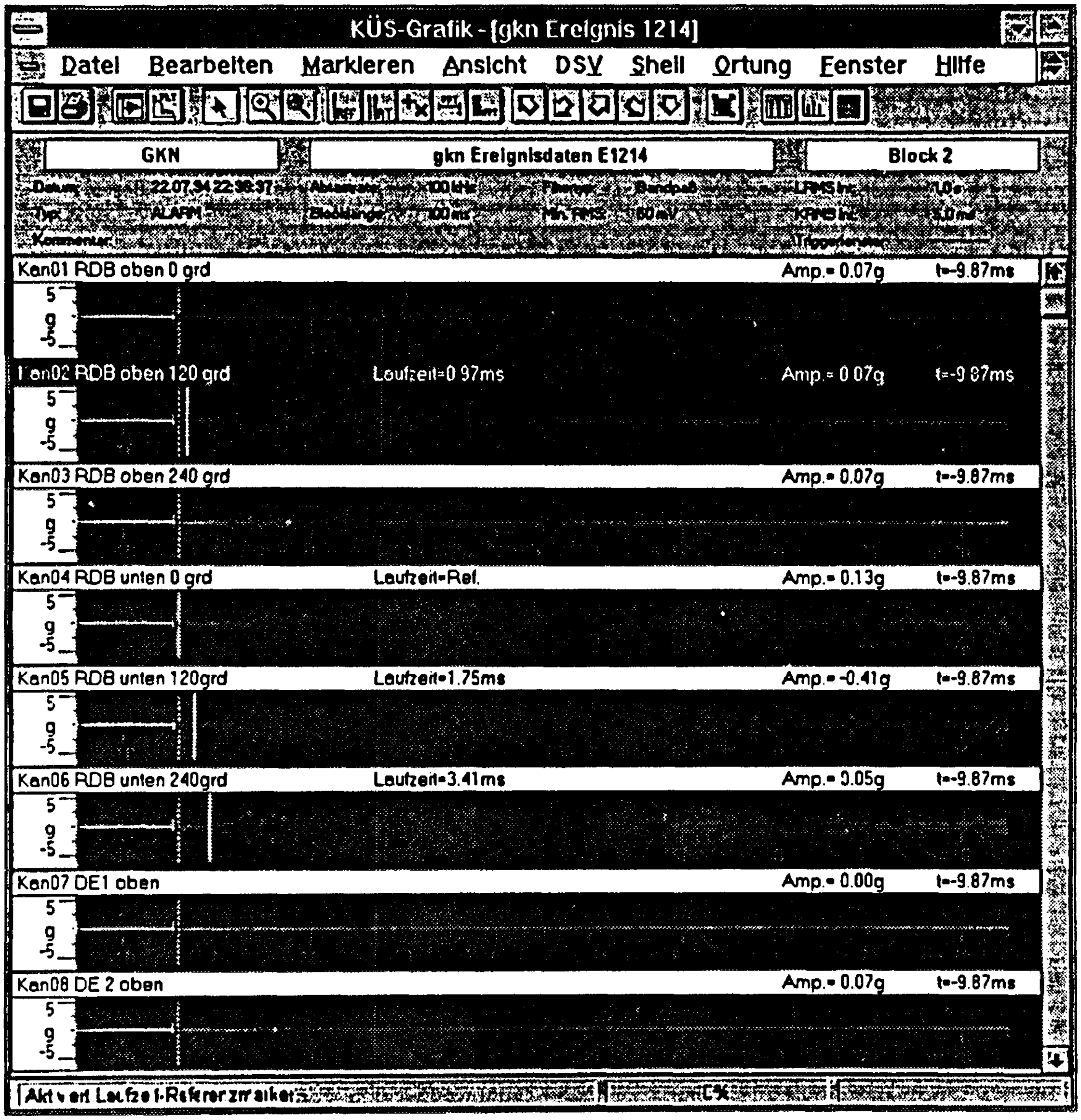

Fig. 1: Example of an 8 channel acoustic event

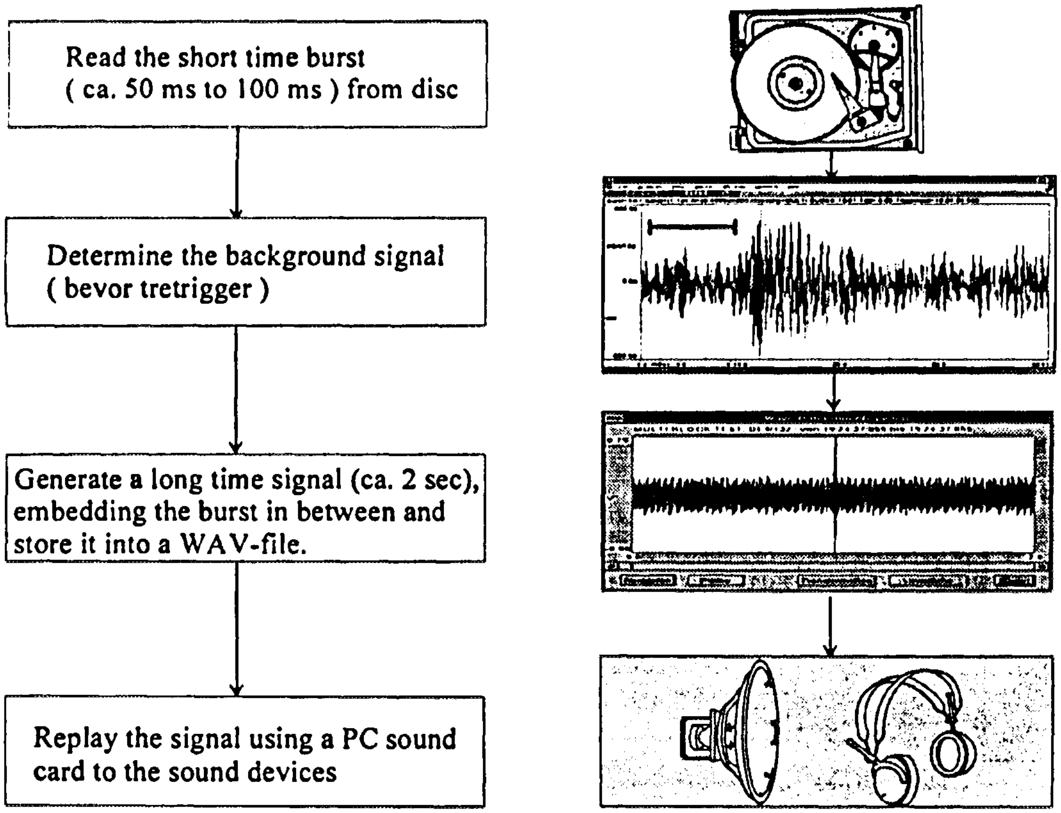

Fig. 2: Block diagram of the ISTec puzzle technique

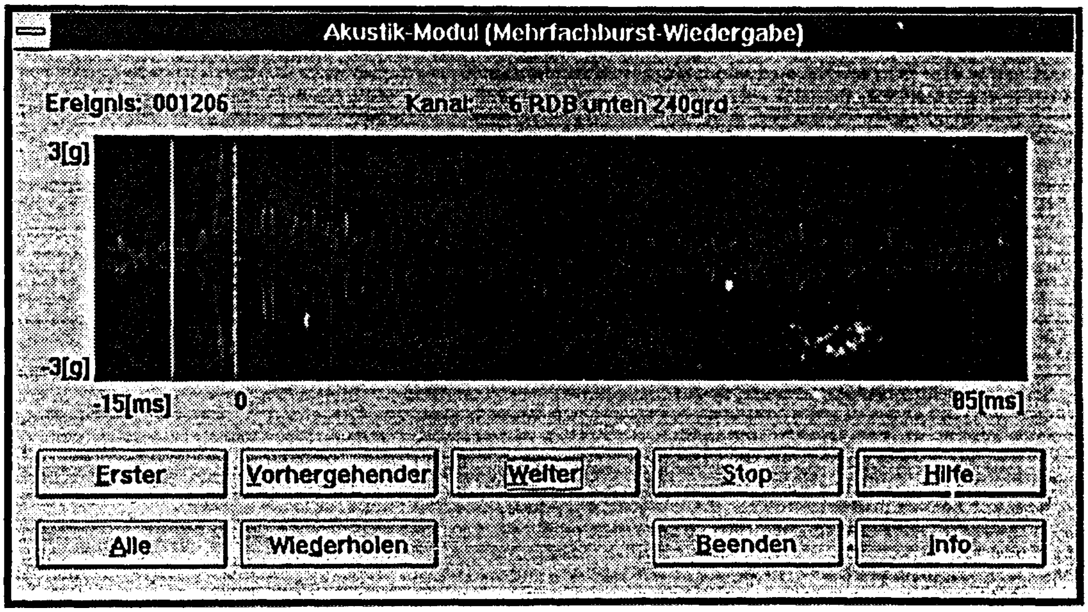

Fig. 3: User dialogue for the ensemble replay

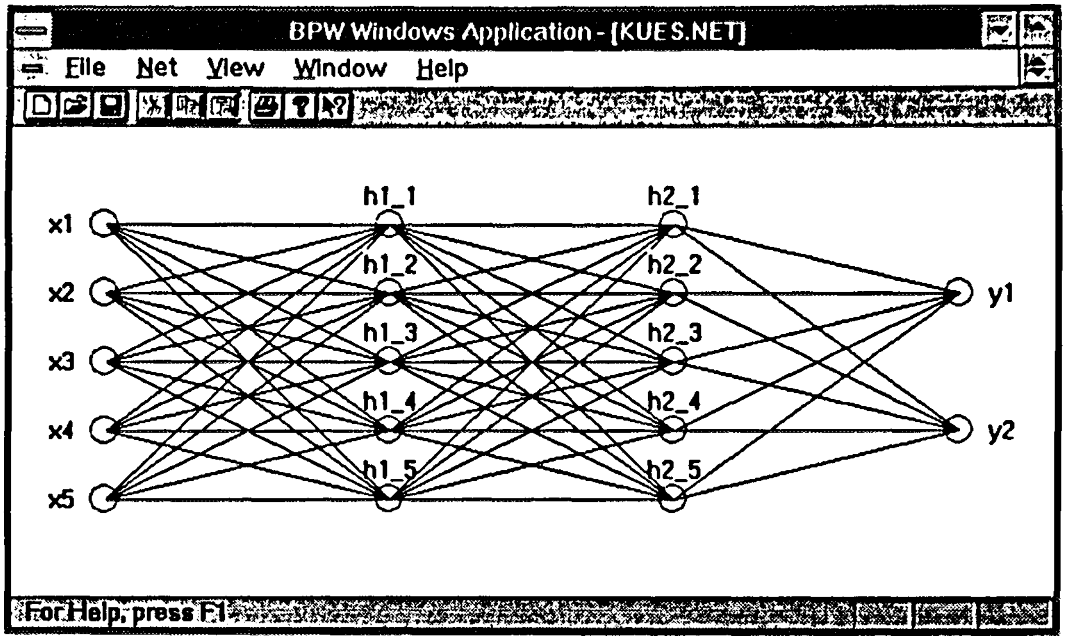

Fig. 4: Structure of the neural network

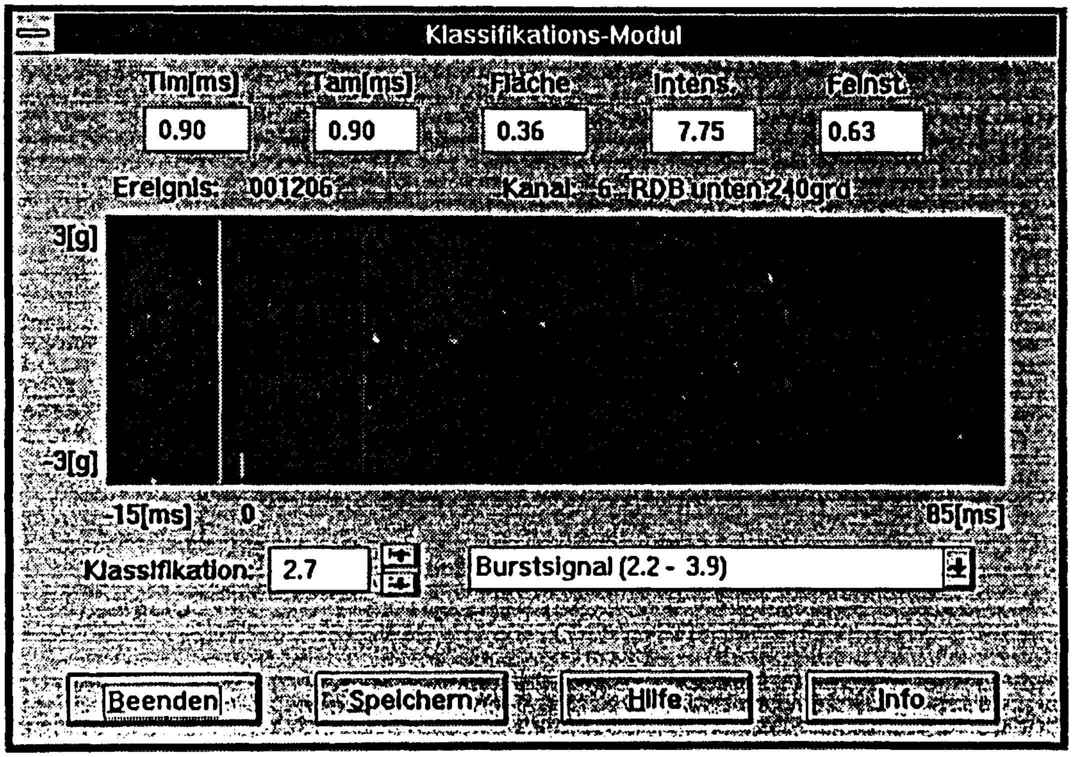

Fig. 5: User dialogue for the single event classification

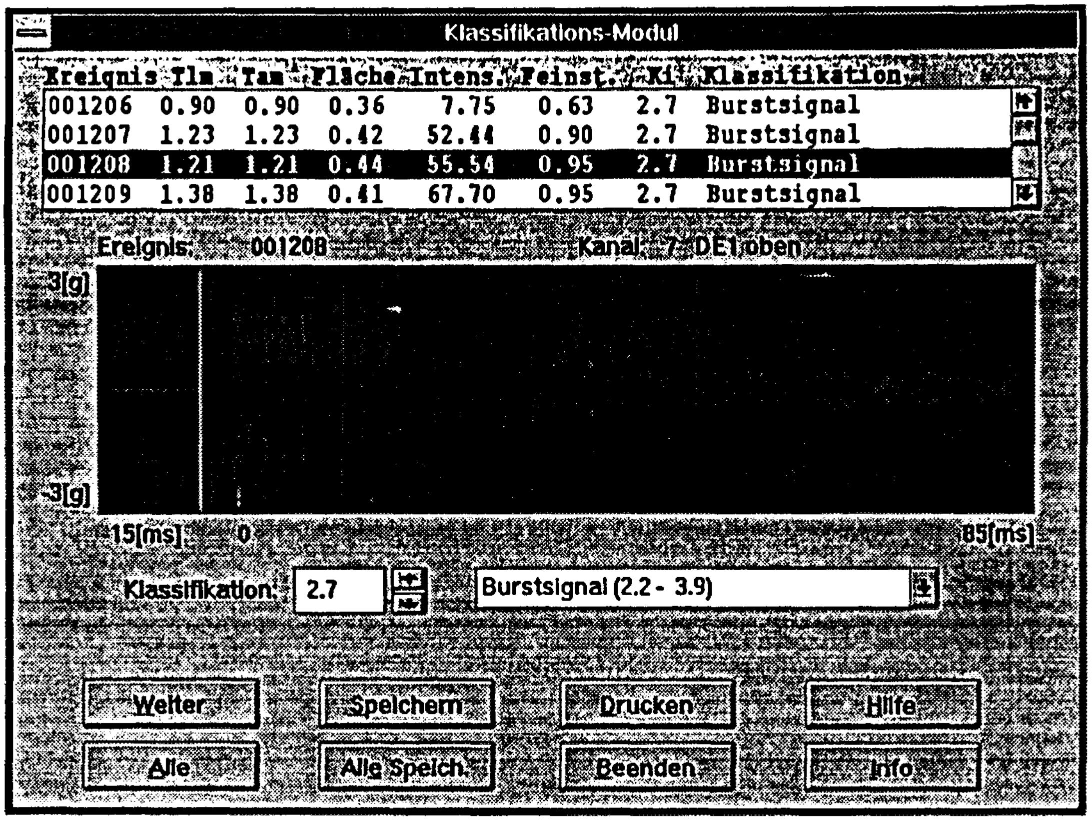

Fig. 6: User dialogue for the burst ensemble classification

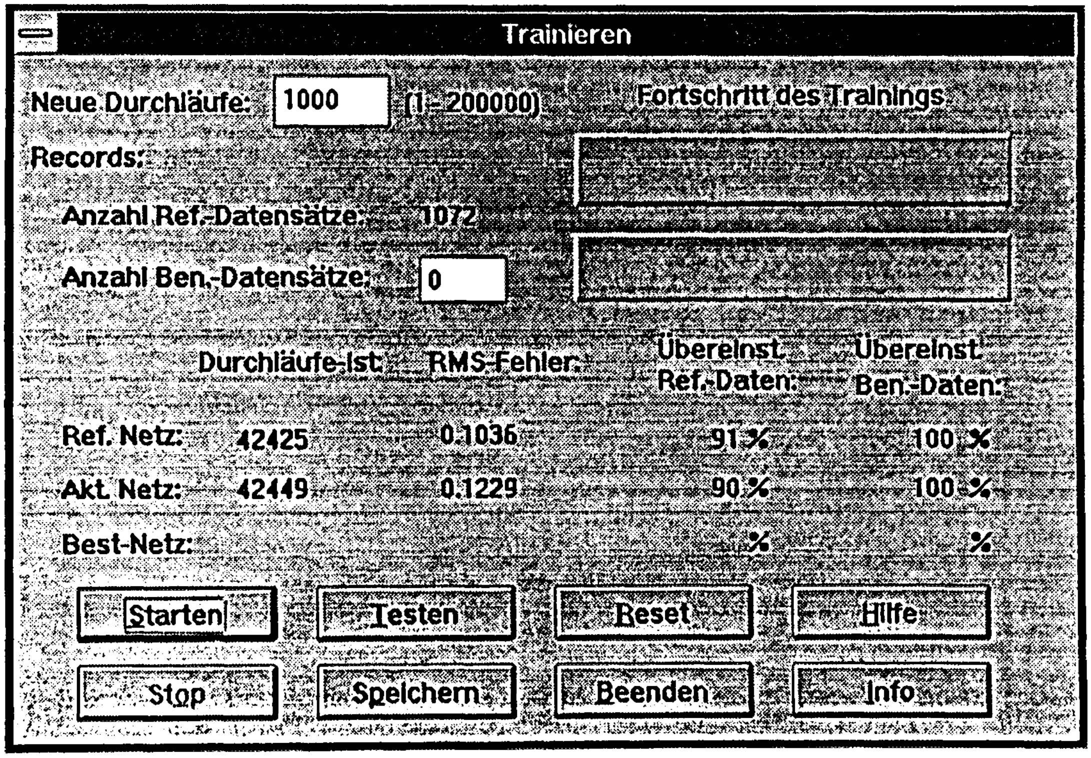

Fig. 7: Training dialogue for the super user

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Session 5
Panel Discussion

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SESSION 5

PANEL DISCUSSION:
HOW TO IMPROVE THE IMPACT OF DIAGNOSTICS ON NPP PERFORMANCE AND SAFETY

Chairpersons: Mr. G. Por, Hungary
Mr. J.L. Fowles, U.K.

1

PANEL DISCUSSION: HOW TO IMPROVE THE IMPACT OF DIAGNOSTICS ON NPP PERFORMANCE AND SAFETY.

Summary of the Panel Discussion

Participants discussed the topics, 'How can we improve the impact of diagnostic systems on the safety and reliability of nuclear power reactors?' and 'How can we improve the effectiveness of diagnostic systems?'

The first important issue raised in the discussion was that diagnostics should be presented in the right way to those staff members who might use its results. The effectiveness of diagnostics depends on the presentation of comprehensive information in a clear and understandable way. It is advisable to use the NPP computer network for future systems.

A second important issue was that diagnostics will only be used in NPP only if it is beneficial for that plant. This means that it must result in a real financial benefit or a clear improvement in plant safety. If diagnostic systems only result in extra problems and no savings than they will not be used. This has already happened in several places.

The third result of the discussion was that standards are going to be distributed for this area of technology and participants should contribute to producing these standards. In addition to his personal opinions in this area, Mr Welbourne prepared a detailed survey of applicable standards, which was sent to the chairmen after the meeting and is included in the annex.

The work started in the framework of the IAEA Task Force on a database for diagnostic systems should be continued. The most important areas for the future are:

- to produce a summary of all successful diagnostic systems with a cost/benefit assessment, also indicate whether these were for permanent installation or to deal with a particular problem,
- to produce a list of existing diagnostic systems and their achievements,
- to elaborate the recommendations on operator displays and the use of NPP computer networks.

We believe that the discussion and personal opinions of contributing participants was interesting enough to publish in shortened form. This is given, as recorded by the chairmen, in the annex with the summary on standards.

Annex: Notes on Personal Contributions on the Subject Made by Participants and Recorded by the Chairmen

This session took the form of a general discussion of the issues raised by the title, 'How to Improve the Impact of Diagnostics on NPP Performance and Safety'. It was lead by Dr Por.

Early speakers addressed the issue of gaining acceptance of new methods from NPP operators.

Mr DeVerno (Canada) discussed the presentation of information to operators and maintainers. Although the trend in Canada was towards all embracing data management systems, it was important to present the right information to the right people in the right way. Presenting the wrong information or too much information was a waste of effort and resources and resulted in confusion and reduced safety.

Mr Craik (Canada) discussed the social effects of the current policies of no new stations and down sizing of workforces. Any diagnostic systems presented as a means of reducing staff numbers would probably meet with some resistance from staff.

Mr Südmersen (Germany) pointed out that resistance would be greater if the new system changed normal operation. They were more acceptable as an aid external to the control room. In his experience, once one operator had been helped by a new system then the problem of acceptance was over. A new technology is likely to be resisted if the operator doesn't understand it. Mr DeVerno introduced the idea of using plant simulators to introduce new diagnostic technology to operators.

Mr Greenway (UK) pointed out that new diagnostic technology must deal with the plant as it is now rather than an idealistic plant which had easily accessible, comprehensive and perfect instrumentation. A realistic plan was needed to move towards the ideal. We should also consider how changes in technology should affect the structures of operators and maintainers on NPP's.

Mr Frick (Switzerland) said that his company produced power rather than maintain equipment. They had alliances with original equipment manufacturers who were given maintenance contracts. The manufacturers understood their equipment better and would introduce appropriate diagnostic techniques. Dr Por questioned whether it was always possible to get manufacturers to maintain equipment. Mr Frick said that competition should be used to ensure that this happens. Mr Greenway and Mr DeVerno had examples of computer manufacturers who would link in to customers computers to assess performance as well as provide maintenance. Although this had not been applied to NPP computers it could be used for other equipment.

Prof. Uhrig (USA) explained that new techniques should be presented to operators in a non-threatening way. He recalled an attempt to introduce Reactor Noise Analysis techniques. The question had been asked "What if all other indications are showing normal but this new technique indicates that there may be a problem? Would you shut down?" The response of the Regulatory Authority had been, "Yes, of course!", and operators had immediately reduced their interest in the new technology. He agreed that operator acceptance was crucial. Operators, and particularly older operators, would resist new technology forced on them. It was necessary to keep new technology simple and to sell the advantages to the operator.
Prof. Uhrig agreed that careful thought was required before more displays were presented to the operator. We should ask, "Are they really necessary?". Mr DeVerno said that it was a Regulator requirement that the benefit of all new systems should be demonstrated. This must include a Human Factors assessment.

Mr Welbourne (UK) examined the characteristics of an operator interface. The output to the operator must not be dangerous and must be trusted by the operator. Human Factors must be used and the operator should have an intuitive grasp of the processes involved. Simple alarms are usually easy to understand, plant models can be made understandable but he questioned whether neural networks could be. He also stressed that we should look for what operators need rather than what we would like them to need.

Dr Por asked whether operators needed Loose Part Monitoring Systems. Mr Ding responded that he had never experienced a loose part but that the system was still necessary for safety and could be used to monitor for other events such as pump impeller impact. He pointed out that new systems must be simple for operators to understand to be accepted but once an operator had accepted a new system they were proud of them. These systems were usually the first that the operator would demonstrate to visitors.

Mr Südmersen supported the view that maintainers of equipment would be most interested in the new techniques. He agreed that a simple interface was important for everyone, even experts.

Dr Por raised the question of international standards for the various techniques. Mr Welbourne is a member of international committees on standards and ran through the standards requested by Mr Dusic in his paper to the conference. The known position at that time was:

1. Work on vibration monitoring for structures and machinery is in the scope of ISO/TC108. Mr P Theodor of Switzerland is a member of that committee and may be able to provide liaison with the IAEA Task Force.

2. Loose parts monitoring is covered by IEC988 - Acoustic monitoring systems for loose parts detection. Dr Y Ding of ISTec said that work was needed on a supplement to cover digital processing and event location methods and it was suggested that he could pass a scope of work to the German national committee for consideration.

3. Leakage Monitoring is covered by IEC1250 - Nuclear Reactors - Instrumentation and control systems important to safety - Detection of leakage in coolant systems.

4. Monitoring of valves is not specifically nuclear, and ISO or IEC/TC65 may be doing relevant work.

5. Core Diagnostics will be addressed by the French draft IEC1502 - Pressurised water reactors - Vibration monitoring of internal structures. A contribution from Dr G Por could be valuable in developing this standard. There is current work on SPND detectors as 'in-core detectors for neutron flux measurement in power reactors'. IEC568 - In-core instrumentation for neutron fluence rate (flux) measurement in power reactors and IEC737 - In-core temperature or primary envelope temperature measurement in nuclear power reactors are also relevant.

6. Signal validation work is proposed, and currently awaits national votes in June, and nomination of experts. The UK proposal is IEC document 45A/226/NP of March 1996, and the title was agreed as 'Nuclear power plants - Measurement validation for critical safety functions'. This restricts the scope to a manageable amount of work. Mr E Quinn of USA had agreed to be project leader if the work is approved, and Mr Welbourne can put any interested members in touch with him.

Mr Welbourne pointed out that standards are written in the IEC by individual interested engineers and experts, nominated by their national committees for standards. Since the IAEA group had asked for some standards to help their work as engineers, the contribution of its expert members to IEC work would be of great value.

Prof. Uhrig indicated that cost is becoming vital to NPP operators, as for everyone else. There is a move towards performance based maintenance and that needs predictive systems. Sensor validation and calibration can save money on calibration, especially inside containment. A valve monitor to check for operability is much cheaper than the regular dismantling of valves. Bearing monitoring to predict failures will save money. Inferential measurements can avoid sensor drift (eg venturi fouling) causing down rating of plant. Models plus sensitivity analysis can improve plant efficiencies. Relating diagnostic systems to money saved is often a good way to get them accepted.

Dr Ciftcioglu (Turkey) thought that we must use statistics to get information from plant and would like to see all plant signals provided in a stochastic form for analysis. He thought that people were frightened by new technology but it had made many complex analysis techniques possible. He recognised the licensing problems associated with computer software but the information it made available would be better.

Mr DeVerno said that plant was licensed on the basis of installed instrumentation and that it was not necessary to increase measurement accuracy beyond that point. New technology should demonstrate that the licence conditions were being met. New techniques would not be applied to NPP's if they were not beneficial. This meant improving safety and performance and reducing shutdowns and maintenance. He cited multivariable control theory which was widely used in industry but not in NPP's. Any technique is only as good as the money and safety improvements that it generates.

Dr Kossilov (IAEA) agreed that acceptance by users is essential and that the technique is not important only its usefulness. He did not want to rule out neural networks, however. He compared the suspicion that computers were treated with in the early days and pointed out the impact that they now had. Advanced methods should be promoted to spread understanding.

Dr Kossilov explained that eighteen months ago a request was received from Eastern Europe for presentations on plant diagnostic techniques. We should now look at what IAEA can do at national levels. Members were asked to write to Mr Kossilov to say what support was needed at the practical, working level.

The Task Force needs to recommend standards and IAEA can organise questionnaires and meetings to promote this. Each technique needs a cost and safety analysis to help to promote it and this should be provided in an advisory document. A collection of experiences in the use of techniques could be made and disseminated. At the November Technical Committee Meeting a database service was suggested and this could be provided. For example a VVER database could be useful, pooling knowledge of problems with components so all could benefit from the shared experiences. A lot of discussions on improvements to safety are required.

Mr Greenway thought that there was a need to establish good and bad practice in NPP diagnostics. Methods of justifying techniques needed to be established. On the major recommendations from the International Task Force on NPP Diagnostic's he thought that the first should be extended to safety, he would endorse the second on database development and on the third he felt that there were too many standards already.

Dr Ding thought that the IAEA could do more to improve contact between eastern plant operators and technologists in the west. In particular he would like feedback on the use of western equipment in the east. A loose parts database would also be useful for him.

Mr Südmersen would like help from IAEA in translating documents in to Eastern European languages. Dr Kossilov said that this was a commercial matter and did not involve the IAEA. Mr Südmersen felt that at least abstracts from western papers could be translated and disseminated. Dr Kossilov thought that good practice information could be sent out.

Mr Korolev (Russian Federation) said that there were two classes of system; those important for safety and operator aids. Each Russian Federation NPP has step by step operating procedures based on a safety analysis. These are produced by the designer and approved by the regulator. To implement a new system it is necessary to show improvements in safety and performance and how this will be achieved. If it will improve safety then the designer should make changes to the safety case. If the case is approved by the regulator then the improvements are made on all plants of that type. Systems should be able to be used automatically without the need for an expert on the site. Implementers should share responsibility for the system and take responsibility for identifying faults that could be introduced by their system. There should be one team working together.

Mr Yastrebenetsky (Ukraine) said that European Union help was being sought for two new units in the Ukraine and that diagnostic techniques could be applied to these where appropriate.

Mr Brendeford (Norway) thought that an IAEA Task Force should produce recommendations for the implementation of diagnostic systems on NPP's. These should include:

Why do we need them?
Who should use them?
How much will they cost?

There should be a clear definition of the terms diagnosis, alarm and monitoring. Diagnosis should explain why there is a problem.

Mr DeVerno added that the question 'What is the benefit?' should be addressed. A database must identify where the improvement will occur - improvements in safety being the key issue.

Mr Bindon (UK) said that the UK NII was only interested in the plant running safely or being shut down safely. Nuclear plant is built to produce electricity and that is important too. They must be safe and they must make money or they would not continue to operate.

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