# DISTRIBUTED HMI SYSTEM FOR MANAGING ALL SPAN OF PLANT CONTROL AND MAINTENANCE

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Digitalization of not only non-safety but also safety-grade I &C systems with full computerized Main Control Room (MCR) is the recent trend of I&C systems of nuclear power plants (NPP) around the world, while plant maintenance has been shifting from traditional time based maintenance to condition based maintenance. In order to cope with the new trend of operation and maintenance in NPP, a concept of online distributed diagnostic system for both plant operation and maintenance has been proposed in order to further improve both the plant efficiency and the work environment of plant operation staff members by organizational learning. In this respect, the research subjects of human machine interface (HMI) for the online distributed diagnostic system are also discussed for supporting the plant personnel at both MCR and local working places in the plant by the application of advanced ICT (Information and Communication Technologies).

**KEYWORDS** : Distributed Online, Diagnosis System, Operation, Maintenance, FMEA, GO-FLOW, MFM

## 1. INTRODUCTION

### 1.1 Motivation

These days, the extension of reactor operation periods and plant life extension is the worldwide trend for efficient and economical operation of nuclear power plants. Plant maintenance methods have been changing from the traditional time-based maintenance (TBM) or periodical shutdown maintenance (where reactor operation is stopped and all the equipment is checked, disassembled, tested, and assembled again or exchanged in accordance with the prescribed procedure) to condition based maintenance (CBM) or risk informed maintenance [1].

In the case of CBM, online condition monitoring methods are positively used during power operation; that is, all the important equipment is continuously or intermittently monitored during plant operation to check their status and predict their future trend to judge whether or not it is necessary to conduct maintenance work during the next reactor shutdown period. In the US, even online maintenance of failed equipment is conducted. In order to cope with this new requirement it will be necessary to develop a new method of human-machine collaboration by applying new ICT for developing intelligent monitoring system which will help humans to monitor all equipment, diagnose equipment state, and conduct complex planning analysis for both operation and maintenance of nuclear power plants.

### 1.2 Next Generation Human Machine System Project

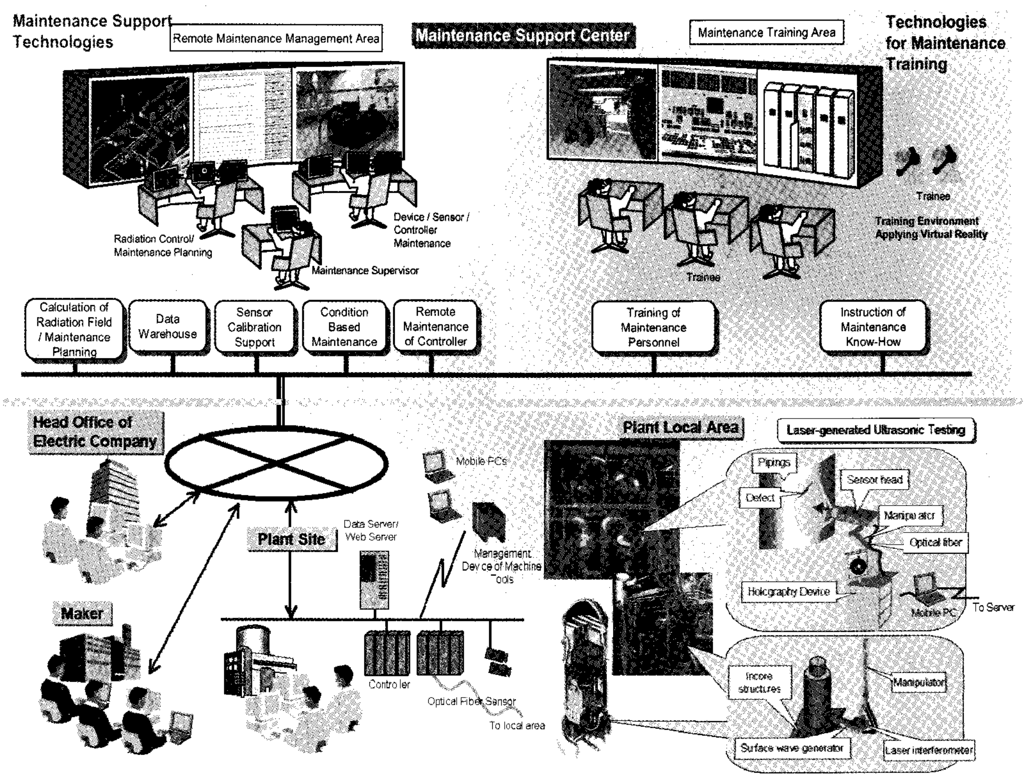
The motivation mentioned above was first but only partly tackled by a METI (Ministry of Economy, Trade and Industry) Supported Project called "Next Generation Human Machine System Project". This project was conducted for three and a half years between 2002 and 2005 by the cooperation of many university researchers in the field of human machine interface in Japan with the colleagues of Mitsubishi Electric and Heavy Industries[2]. In this project, the key concept was the remote operation & maintenance support center created by the integration of Operation and Maintenance (O&M) management for common sharing of O&M functions for multiple plant units. The integrated Main Control Room (MCR) in a remote O&M support center was proposed for remote operation and monitoring of all plant units where only a few O&M staff members will reside. The Remote O&M were assumed to be a new style of plant O&M work in future, which will be realized by developing (i)intelligent operation support system, (ii)intelligent communication software technology, (iii)advanced human interface devices, and (iv)the related advanced knowledge base (KB) for O&M Information in the current practice of nuclear power plants. The concrete subjects of the related research and developments were (i)Dynamic Permission System for operator's direct control actions [3], (ii)Conversational Agent System for the co-worker of operators at MCR [4], (iii) application of augmented reality technology for supporting maintenance workers [5] and (iv)Daily maintenance support by ubiquitous network and wearable hand-held devices [6].

### 1.3 Flexible Maintenance System Project

Following several ABWR plants in the 90s in Japan, the full digital I&C system with computerized MCR was implemented in a commercial PWR (Tomari Unit 3 at Hokkaido Electric Power) [7]. Then, a turning point or change of direction of research and development from operation to maintenance in the area of nuclear power instrumentation and control in Japan was the year 2000. The Five Year Project of Flexible Maintenance System (FMS) started in 2000 with the union of four industries: Toshiba, Hitachi, Mitsubishi Heavy Industries, and Mitsubishi Electric, with the cooperation of many I&C industrial researchers and engineers working towards the innovation of maintenance and renewal technologies of nuclear power plants. The motivation of the FMS project can be summarized by the following two points: (i) Grasp human and machine as the whole system in order to improve human and organization factors by the introduction of advanced technologies of sensing, control, and information processing, (ii) Reduce the O&M cost by the adoption of ICT for remote operation for overall plant operation and maintenance. The twenty individual technologies were developed by the FMS project, and will serve to improve both the maintenance work and training of workers. [8] The results of FMS project and the prospect of their application will be summarized in the following sub-sections.

#### *1.3.1 Advanced Maintenance Technologies*

Three technologies were developed in order to improve maintenance work during plant outage. They are: (i) technologies to save human work for maintaining equipment (maintenance-free sensor, multi-point sensing system by optical fiber, radiation visualizing camera, support systems for sensor calibration, and enlarging sensor calibration period), (ii)remote non-contact sensing technologies (laser-induced ultrasonic defect sensing systems for narrow places, broad area and complex shape area, intelligent detection by image sensing, evaluation system for radiation distribution and exposure dose), (iii)remote maintenance technologies (security network, remote maintenance system for plant control units), (iv)intelligent maintenance management technologies(support system for condition monitoring and condition based maintenance, automatic management of maintenance tools, data warehouse of design information for large machines and electric equipment, data warehouse for maintenance related information).




Product Overview of Flexible Maintenance Support System Project

Fig. 1. Image of FMS Project Products Application

### *1.3.2 Advanced Training Technologies*

By applying Virtual Reality (VR) technology, two technologies were developed for exploiting advanced training methods. These are: (i)mastering maintenance know-how (maintenance work for large machines, electrical equipment, and I&C systems), (ii) describing plant working environment in VR (visualization of plant in-situ work such as maintaining reactor core lower support structure, collaborative work between control room staff and in-situ worker to calibrate I&C system).

### *1.3.3 Image of FMS Technologies Application*

A visualization of the application of various products by FMS project for real NPP is illustrated in Figure 1. As seen in the lower right-hand side of Figure 1, the laser-induced ultra-sonic defect sensing systems can offer new defect detection technologies for narrow place, broad area, and complex shape area, which are difficult to measure by the conventional methods. Also, it is seen in Figure 1 that the formation of a broad-area information network system over plant local site, headquarters of electric power company, and the "remote maintenance support center" will serve to improve the maintenance management in nuclear power plants.

### 1.4 Human Factors Problems in Digital MCRs

On the other hand, for the development of various elementary technologies proposed by the aforementioned two projects to innovate O&M work environment, real application of full digital I&C systems with the introduction of computerized MCR in the nuclear power plant has been causing new human factors issues. That is mainly caused by human-machine interface (HMI) design of MCR, although it has contributed to improve the operators' workload. Especially it has been pointed out by the Western community of engineering ergonomists that the main problem of present-day computerized MCR is the poor communication between individual operating staff members in the MCR and the difficulty of judging another person's work at MCR. [9]

Another issue was observed by the author in a new fully digitalized MCR of a Japanese PWR plant now almost starting to operate. That is the provision of a maintenance console layer which is added in the MCR to the two conventional layers of operator console layer and large screen display. (The common feature of computerized MCR is a combination of (i) operator console layer for individual operators (reactor operator, turbine operator, and operator supervisor) and (ii) a large screen display for information sharing by all operators). According to the staff members at the PWR plant, there are two reasons for introducing the maintenance console layer: (i) paper tags traditionally used for indicating the status of equipment isolation during the maintenance work cannot be used in the fully digitalized MCR, and (ii) the necessity of software maintenance (visualization of software logics).

Those real situations in the modernized MCR have in the past also motivated the author of this paper to re-think the Human-Machine Interface (HMI) design issues for the proposed whole distributed system concept; however, such a system has not yet been realized. In this paper, although not yet a complete one, the process of the author's review of the HMI design methodology will be reported for an open discussion with respect to the method of implementing it for the whole distributed system concept. In the items that follow, the introduction of the whole distributed system concept is accomplished, followed by the results of a review study of the HMI design.

## 2. WHOLE DISTRIBUTED SYSTEM CONCEPT

### 2.1 Basic Concept

The operation and maintenance of a nuclear power plant is thought to be very complex, but, fundamentally it is an intelligent and creative activity such that is based on (i) the multi-layered versatile knowledge of "objective", (function", "behavior", and "structure" of the target system and equipment to be operated and maintained (mental model), with applying (ii)broad expert knowledge such as cause-consequence relations of system and equipment failure, how to find symptoms of failure from the various sensor signals, and how to predict failure progression by measuring and processing (iii) many sensors both in existing plant instrumentation from time to time, as well as those done by extra measurement devices brought in occasionally to the plant in the case of normal shutdown period or online monitoring by in-service inspection or in post accident shutdown examination, in order to judge (iv) whether or not the levels of defense-in-depth (DiD) are still maintained or not. Here you should note that there are various automatic safety control systems implemented in the whole system with partly manual operation by operators for the steady state of power operation,.

The "cognitive activities" by both the operators and maintenance workers can be summarized as the repetition of four types of work (i) to (iv). Wherein item (i) (the original implicit mental model in the human brain) is central and is externally expanded into items (ii) and (iii) ("explicit expertise knowledge and skill of the workers) and finally reaches item (iii)(Judgmental issue).

The distributed online support system for both operation and maintenance will be exploited by using advanced IT and the knowledge of cognitive systems engineering so that the usage of the system can effectively stimulate the plant workers' intrinsic "organizational learning" [10]. The utilization of the system will be a collaboration by multiple workers with task allocation depending upon the individual workers' experience (skill and knowledge). The modification of the systems function should be easily made by maintenance workers.

## 2.2 Basic System Architecture

The basic system architecture of the whole online distributed diagnostic system for both the operation and maintenance proposed in this paper can be seen illustrated in Figure 2.

The whole online distributed diagnostic system is assumed to be shared by both the operating and maintenance staff members via the plant intranet, which will connect main control room and various places of major machines and equipment comprising nuclear power plant. Here also it is assumed that the MCR is a fully digitalized control room where a large display screen is equipped for the purpose of information sharing while two kinds of console are arranged both for operation and maintenance.

The major sub-systems comprising the whole distributed system are two kinds of server and three kinds of client, as will be described below individually. Those software entities are connected to the plant intranet, which should be of high reliability with cyber security.

### *2.2.1 Plant Data Server*

The data for the plant server will come from various sensors of various equipment of both built-in instrumentation and extraneous devices temporarily attached by maintenance workers for testing measurement. The data coming from those various sensors may be formatted according to different codes. Therefore, those individual data formats should be converted to a unified protocol by a suitable piece of middleware so that the data running on the intranet can be read and utilized easily and freely by various servers and clients for their specific activities.

### *2.2.2 Plant O & M (Operation and Maintenance) Knowledge Base Server*

The broad knowledge base on plant operation and maintenance should be stored, updated, and used by plant personnel via their intranet. As already stated in the first part of **2.1**, the central knowledge base for maintenance will be the multi-layered versatile knowledge of "objective", "function", "behavior", and "structure" of the target system and of the equipment to be operated and maintained.

There is also broad expert knowledge such as cause-consequence relations of system and equipment failure, how to find symptoms of failure from the various sensor signals, and how to predict failure progression. Various troubleshooting information should be used as the data sources to reduce the relevant knowledge bases. They can be derived by (i) real experience of plant troubles, and (ii) knowledge of possibility of "risk" derived by general technical methodologies. The representative sources of trouble information are: (i)real trouble cases, (ii) risk analysis information such as FMEA (Failure Mode and Effect Analysis) tables, FTA (Fault Tree Analysis) graphs, etc., (iii) design standards and technical guides, (iv) engineering reports, (v)technical papers, journal papers, books and websites, and (vi)unspoken knowledge stored in the brains of designers and engineers.

The relevant knowledge bases should be acquired and be described so as to be used commonly by the organizational learning activity done by the collaboration of both the operation and maintenance staff members. One type of such knowledge to be taken into account will be the cause-consequence chain of troubles as depicted

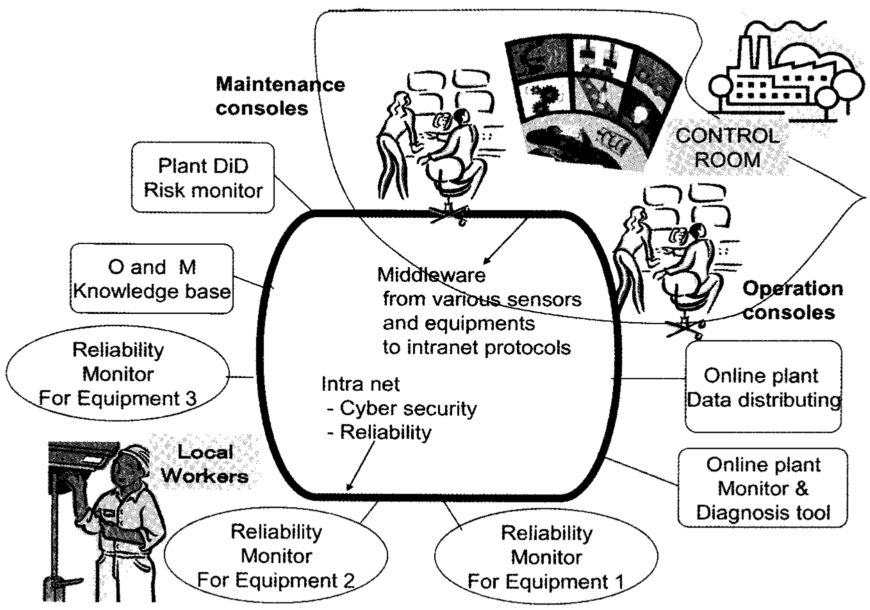



Fig. 2. Whole Online Distributed Diagnostic System

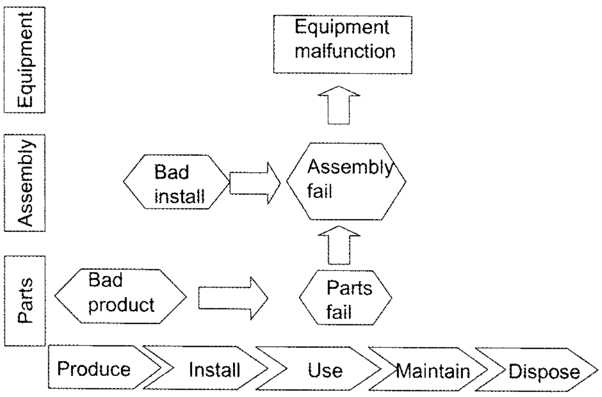



Fig. 3. Cause Consequence Chain of Troubles in Plant Life

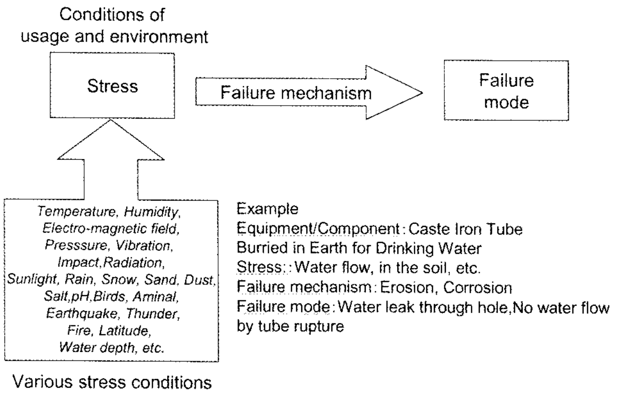



Fig. 4. Stress-Failure Mechanism-Failure Mode Relationship

hierarchically with respect to structural formation (perpendicular direction) while chronologically in plant life (horizontal direction) in Figure 3.

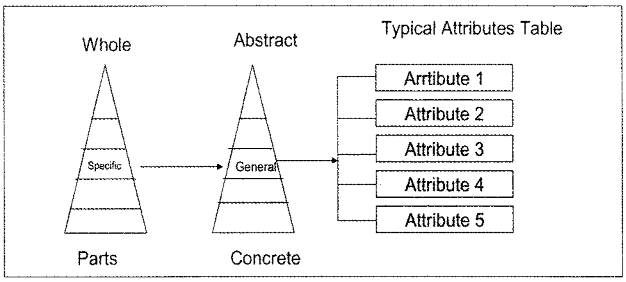
Also taken into account is the frame of understanding the various phenomena of failures. This could be described as "stress-failure mechanism-failure mode" relationship as illustrated in Figure 4.

Further, it will be necessary to reduce and assemble the knowledge base from various troubleshooting information. This knowledge on the causal relationship of failure mechanisms should then be compiled in the database of the stress-failure mechanism-failure mode relationship, wherein the following items should be included:

(i) Hierarchical categorization of various stress conditions of usage and environment,
(ii) Hierarchical categorization of various physical and chemical mechanisms of failure,
(iii) Description of failure progression modes from incipient (elementary) phase to higher phases of the developing the failure mode such as diffusion of impurity in Phase I, degradation of mechanical strength in Phase II, and crack and rupture in Phase III,

| KB Name | Defined attribute | Failure mode | Stress | Failure mechanism | Controlled attribute |
|---|---|---|---|---|---|
| | | | | | |
| | | | | | |
| | | | | | |

(a) Structured KB for stress-failure mechanism-failure mode




(b) Knowledge base of item' s specification

Fig. 5. Examples of Structuring Knowledge Bases

(iv) Other related knowledge such as principles or models to describe failure mechanisms, examples of typical parts, equipment and components that exhibit such failure, ways of detecting and estimating the rate of failure mode, etc.

Also taken into account for constructing the plant O & M KB is that individual knowledge of "stress-failure mechanism-failure mode relationship" should be well structured: (i)segmented, (ii)generalized, and (iii) correlated so that the knowledge bases can be re-utilized for various purposes such as reducing FTA graph, FMEA table, etc. [11].

Two examples of how to construct such KB are illustrated in Figure 5 (a) to describe equipment information from minute parts, and (b) to assemble KB of various failure knowledge. This way of forming two kinds of KB will be used for generating FMEA table.

The roles of integrated O & M planning staff in the MCR will be to conduct both short and long range planning, which will cover (i)safety evaluation of facility repair and replacement work, (ii)planning in-service inspection and testing program, (iii)risk evaluation of outage work schedule, (iv)risk monitoring at power online maintenance, etc.. For those purposes, living PSA will be conducted as routine work of risk monitoring task. The provision of plant O & M knowledge server should include the supporting tools and the relevant database, such as machine failure rate and human error rate.

### 2.2.3 Clients for Online Plant Monitor & Diagnosis Tool

This client will be equivalent to COSS (Computerized Operator Support System), as shown in Figure 6, where the digital automatic system is the first loop of control comprising non-safety and safety grade, while COSS is

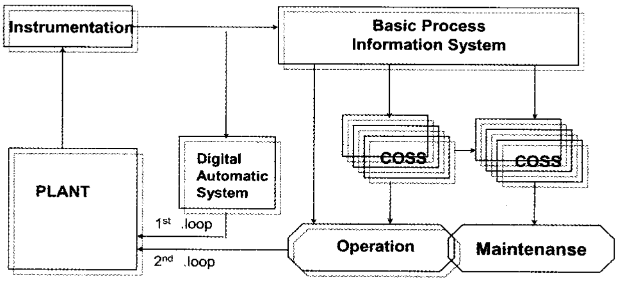



Fig. 6. Computerized Operator Support System

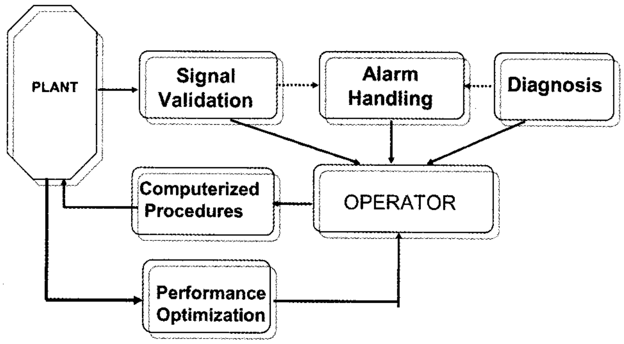



Fig. 7. Five Functions of Computerized Operator Support

deemed as the second loop control of the plant through human operator by the help of various supporting tools. When full digital control systems are implemented in the first control loop, it will become important to verify and validate the software reliability.

For part of the 2nd control loop in Figure 6, there are basically five different functions for the computerized operation support system, i.e., (i)signal validation, (ii) alarm handling, (iii)diagnosis, (iv)operation procedure display, and (v)plant performance monitoring, as shown in Figure 7. The typical examples of various practical software tools used in actual nuclear power plants worldwide for COSS can be seen in Ref .[12]. In this part, functional validation of various tools will also be important because operator might not rely on the support tools unless these tools could give not only true but also useful support information.

### 2.2.4 Clients for Individual Equipment Diagnosis

Individual equipment is monitored by measuring and processing many sensors in the existing plant instrumentation from time to time, as well as by extra measurement devices brought in occasionally to the plant in the normal shutdown period or online monitoring by in-service inspection or in post accident shutdown examination. Risk monitor will be used to judge whether or not the levels of defense-in-depth (DiD) are well maintained. This work will be supported by the clients for individual equipment diagnosis.

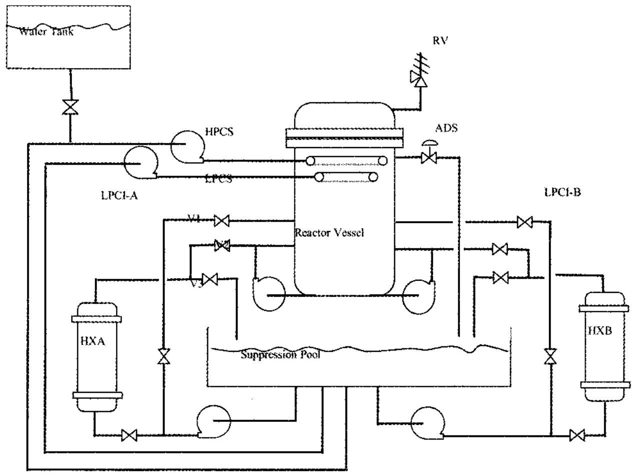



Fig. 8. ECCS System of BWR Plant

The number of clients will change in accordance with the amount of equipment in the target system as well as the number of maintenance staff.

A small scale example of the above client has been developed by the authors [13], for the reliability evaluation of ECCS of BWR as shown in Figure 8. A system reliability analysis method called the GO-FLOW model [14] was used for calculating time versus reliability curve when ECCS was assumed to be triggered to cool down the reactor safely in the event of loss-of-coolant accident. The GO-FLOW model software includes computing capabilities of treating phased mission, common cause failure (parametric models such as ß factor, multiple Greek letter, etc), and uncertainty band evaluation of top event occurrence.

The functional modeling method called MFM (multilevel flow model) [15] was used for developing the user interface to execute the GO-FLOW program. With the utilization of the MFM model, the various interface functions for GO-FLOW software functions such as (i)editing MFM chart for the ECCS system and then converting to GO-FLOW chart, (ii)editing input data of various parameters for machine reliability analysis by GO-FLOW, followed by (iii)the run-control to display the output data, are all easy to understand. The example user interface of this software is shown in Figure 9, while the calculated unreliability versus time is seen in Figure 10. This MFM based interface mainly consists of a model handler and display, a media player, a state awareness agent, a data/signal monitor, an instruction display, and a consequence analyzer. Further detail is described in Ref. [13].

### 2.2.5 Clients for plant DiD Risk Information

This process is undertaken to obtain the risk information on whether or not the level of defense-in-depth (DiD) are well maintained as a whole; this is done by integrating all

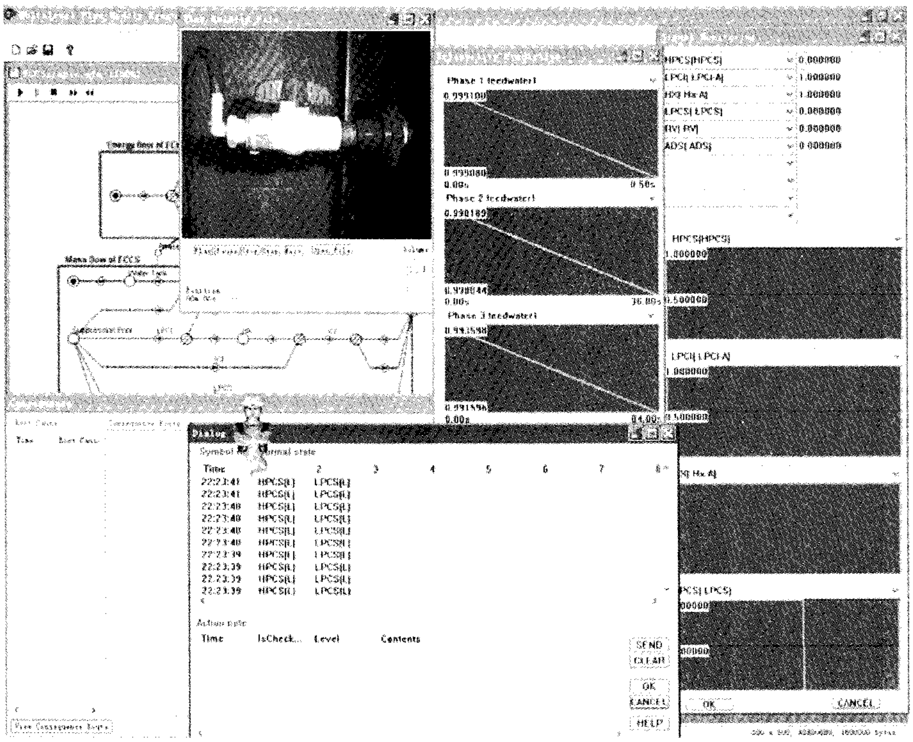


Fig. 9. MFM Based User Interface for GO-FLOW Model

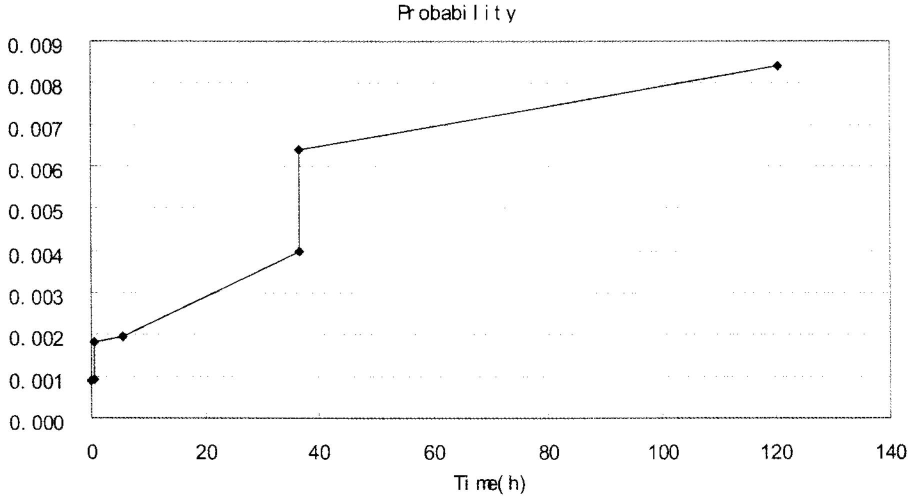



Fig. 10. Calculated Unreliability Versus Time by GO-FLOW Model

the diagnosis results from the clients for individual equipment diagnosis. In order that the online maintenance may be introduced in the real plant operation, the risk monitor should be more accurate and online in real time rather than the case of a constant reactor operation with no configuration change (no online maintenance).

In case of normal plant shutdown until restart of normal operation, the plant configuration pattern will change from week to week in accordance with the maintenance and testing schedule. There will be many hazardous situations during the period of such frequent configuration changes. Such hazardous cases of exposing the uncovered state of reactor core to water, or radiation exposure to the workers might happen by human error. Therefore, to avoid such cases, the risk monitor should be accurate and available online.

## 3. DISCUSSIONS ON HMI DESIGNS

There are many aspects to how to configure the aforementioned whole distributed diagnostic system. In this chapter, the human interface design will be discussed from the aspects of both human factors and the applicable ICT technologies.

### 3.1 MCR Design

A typical control room layout of a fully digitalized MCR in the most advanced PWR plant in Japan is illustrated in Figure 11, while its photo is found in Figure 12. The large display screen is normally composed of two elements of display: one is constant display for showing important plant parameters (plant mimic) while the variable display shows a certain CRT display of the operator console layer by the selection of any operator for sharing focus of attention with all staff members.

Here in this new MCR design, the introduction of a maintenance console layer is the conspicuous feature of this new PWR plant, as was already mentioned in 1.4. This maintenance console layer is mainly used for (i) plant configuration management (indication of valve isolation as the replacement of paper tags in the control room as well as issuing of paper tags to individual valves in the related coolant loops for every phase of outage work) and (ii) software maintenance of the digital control system.

These days, the operation and maintenance of nuclear power plants is changing towards condition based operation and maintenance. There will be a greater introduction of online maintenance at full power operation, and more frequent change of plant configuration for shutdown maintenance with a shorter period than before of whole outage by the use of risk monitor. Therefore, there will be more occasions for configuration change in future NPP operations in order to meet more flexible plant operation.

The configuration management of the nuclear power plant is made by different isolation patterns of valve and pump arrangement in the plant. Since frequent changes of plant configuration by manual operation could be the source of human error, it will be indispensable to introduce a new large screen display to show the whole plant configuration at every stage so that both the operators and maintenance staff members in the MCR can grasp the plant configuration at any time.

Therefore, the introduction of not only the maintenance console layer but also the large display of showing the whole plant configuration will be necessary for part of MCR design in the online distributed diagnostic system.

A comparative evaluation study of various graphical display methods for MCR is under way [16] in which various display methods such as ecological interface display (EID), information rich display (IRD), outage information display (OID), etc, were compared with the traditional P&ID display. In this study, a comparative evaluation has been made from the aspects of operator tasks, plant status, and presentation media. Since the technical progress of ICT is very rapid, it is necessary to take into account the flexibility of upgrading the quality of both hardware and software to improve the HMI of MCR. In this respect, introduction of low cost rapid prototyping and evaluation method of HMI design in a virtual environment will be useful not only for tuning and updating the HMI design by the operating staff members but also for training users to familiarize them with new HMI technologies.

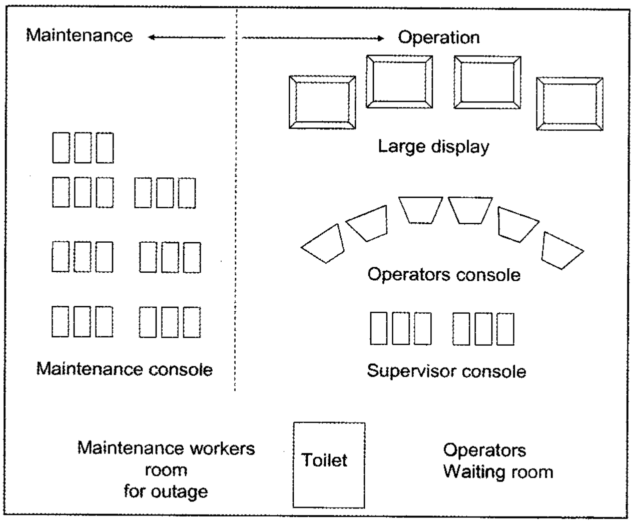



Fig. 11. New Layout of Fully Digitalized MCR of the Most Advanced PWR Plant in Japan (Courtesy of Hokkaido Electric Inc.)

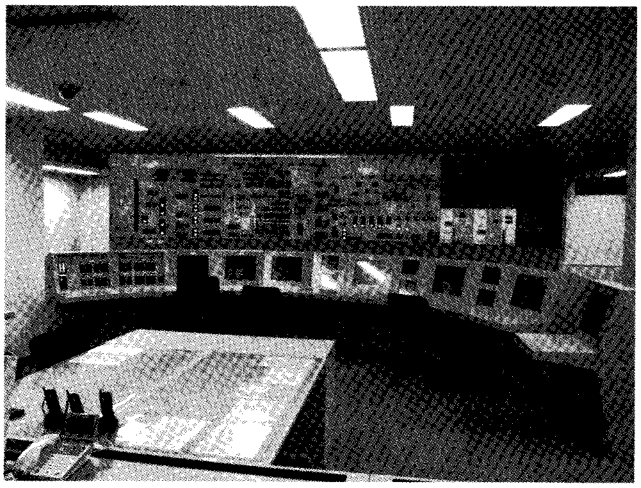


Fig. 12. Photo of Fully Digitalized MCR of the Most Advanced PWR Plant in Japan (Courtesy of Hokkaido Electric Inc.)

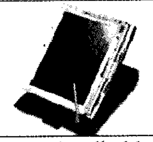
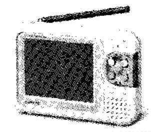
| Device | Dataglass 2 | SCOPO | Glasstron | Tablet PC | Compact TV |
|---|---|---|---|---|---|
| Appearance |  |  |  |  |  |
| Type | Wearable | Wearable | Wearable | Handheld | Handheld |
| Model | Dataglass2. Shimadzu Corp. | SCOPO. Mitsubishi Electric Corp. | Glasstron. Sony Corp. | Travel Mate C100 TMC102I. Acer | SY-4100. Casio Corp. |
| Features | One-eye optical see-through | One-eye video see-through | Both-eye video see-through | 10.4 inch display. 1.4 kg weight | 4 inch display. 0.58 kg weight |

Fig. 13. Five Devices Tested for User Interface of Field Workers

### 3.2 Maintenance Work Support

It is thought that the maintenance workers tasks will change with the introduction of condition basis maintenance. Workers will have to conduct valve isolation tasks before equipment maintenance, and then should go to the designated machine and equipment place without mistake to see the machine's working condition. They will also test, diagnose, repair, disassemble, etc., on site. If various new technologies of remote monitoring and data transfer through optical fiber or wireless LAN are implemented, the maintenance works will be improved.

It is also necessary for the maintenance workers to communicate with the staff members in the main control room. Therefore, they should be more intelligent than in the past about manipulating various high-tech devices for fulfilling their mission when workers enter the plant simply to disassemble, test, repair and assemble many pieces of equipment in prescribed ways within a certain period.

A pilot study on applying augmented reality (AR) technology for the user interface of maintenance workers has been conducted as an experimental study [17]. The objective of this study was to compare various AR interface devices as shown in Figure 13, to find out which device will be suitable for the plant maintenance workers for helping the water valve isolation simulation task in the actual plant as shown in Figure 14. In this experiment, the utilized tracking method for AR was the usage of specially designed artificial markers placed in many places in the plant as landmarks to locate the exact position and direction of the movement of users. Figure 13 shows the specially designed artificial marker, which is placed on the horizontal pipe in the lower part of the figure. The use of an artificial marker was chosen because GPS cannot be used in the building of such a complicated structure. It was found that the compact handheld device, rather than a wearable display, will be favorable to the subjects. It should be pointed out that the HMI of field workers should be usable at their real working conditions by installing various support functions useful for their maintenance activities.

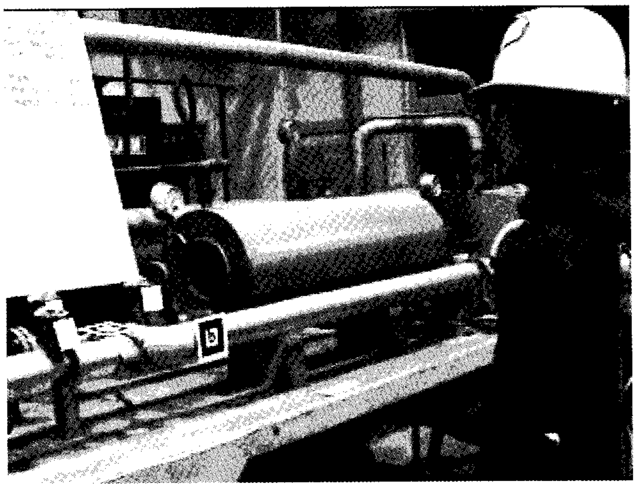


Fig. 14. Scene of Water Valve Isolation Simulating Experiment

The application of a networked virtual environment will also be interesting in studying the collaborative work style between the staff in MCR and the field workers at the machine location. [18]. As shown in Figure 15, the operating staff in MCR will communicate with on-site workers through the network by seeing them as avatars on his/her display. In order to realize this communication system, it is indispensable to locate the exact position of field workers in the plant in real time so that the technical staff members at MCR can give them proper advice for the field workers fulfilling their tasks in the right way.

If this mutual communication is supported by wireless LAN, the positions of transmitters for the wireless LAN may also serve as the proper way of positioning field workers' locations in the plant by applying the "Place Engine" technique [19]. In this case, it is not necessary to paste "artificial markers" in many places in the plant as was proposed by Ref. [17].

In conclusion, to review ICT technologies for maintenance work support, there exist many promising

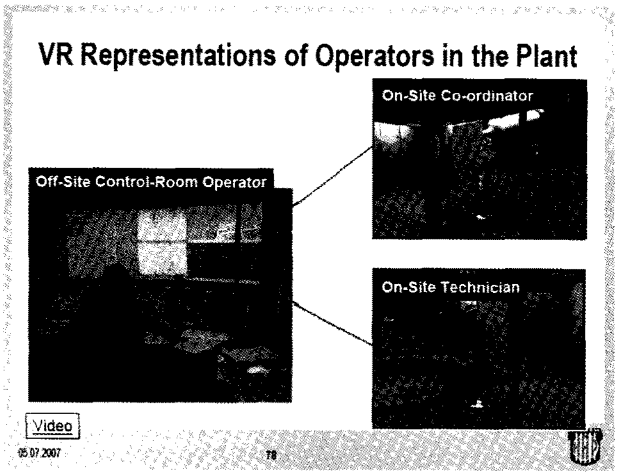



Fig. 15. MCR Staff Communicating with On-Site Co-Workers as Avatars on His Display (From a Video Clip Courtesy of MTO Group at OECD/Halden Project)

methods and techniques already to serve for realizing the online distributed diagnostic system.

## 4. CONCLUSION

A new support system for nuclear power plant operation and maintenance work is proposed in this paper. Although the development has just started, the whole framework of online distributed architecture is presented in this paper, and the method, software development, and discussions of the human-machine interface design were presented for realizing the whole system; all results will be further elaborated so as to be usable in the field.

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