Report on the 14th International Workshop on Nuclear Safety and Simulation

ZHANG Zhijian[1], YANG Ming[1], GAO Puzhen[1], and YOSHIKAWA Hidekazu[1]

1. College of Nuclear Science and Technology, Harbin Engineering University, 150001, Harbin, Heilongjiang, China (yosikawa@kib.biglobe.ne.jp)

Abstract: The 14th International Workshop on Nuclear Safety and Simulation was held on October 23-24, 2012 at Harbin Engineering University (Harbin, China). There were eighteen papers presented by invited speakers from eight countries (*i.e.*, Canada, China, Denmark, Finland, France, Japan, Korea, and U.S.A.), and the total number of the workshop participants was about 60 persons. The subjects of the presentations were: (i) Risk and reliability evaluation of nuclear power system, (ii) Advances in digital I&C and HMIT, and (iii) Nuclear fuels and materials. The summaries of all presentations are compiled in this paper.

Keyword: risk monitor; reliability analysis; digital I&C system; nuclear materials; nuclear fuel cycle

1 Introduction[1]

The 14th International Workshop on Nuclear Safety and Simulation was held on October 23-24, 2012 at Harbin Engineering University (Harbin, China). The purpose of this article is to give readers of this journal (IJNS) a comprehensive summary of this two-day workshop.

2 Workshop program and organization of this report

2.1 Workshop program and participants

The 14th International Workshop on Nuclear Safety and Simulation was organized by the College of Nuclear Science and Technology of Harbin Engineering University. The timetable of the two-days workshop is as shown in Table 1. The list of the workshop organizers as well as the eighteen invited speakers from eight countries (*i.e.*, Canada, China, Denmark, Finland, France, Japan, Korea, and U.S.A.) is listed in Table 2. In addition to the invited speakers, there were *ca.* 40 participants from universities, research institutions and industries from various places in China.

2.2 Organization of this report

The contents of 18 papers presented at the workshop will be introduced in the subsequent chapters by classifying: (i) Risk and reliability evaluation of nuclear power system, (ii) Advances in digital I&C and HMIT, and (iii) Nuclear fuels and materials**.**

Table 1 Time table of the 14th International Workshop on Nuclear Safety and Simulation, October 23-24, 2012

Time	Items	Speakers
	October 23, Tue.	
8:00	Registration	
8:20	Photo taking	
8:40	Opening address	Organizers of WS
9:00	Session 1 Advances in digital I&C Chair: Prof. Morten Lind	Dr. Richard Wood Mr. Koji Ito Prof. Jin Jiang Prof. Zhizhong Li
12:00	Lunch break	
14:00	Report session 1 Chair: Prof. Morten Lind	Dr. He Wang
14:40	Session 2 Reliability evaluation of digital I&C system (I) Chair: Dr. Zen Hai	Dr. Man Cheol Kim Mr. Nguyen Thuy Dr. Jan-Erik Holmberg
18:00	Banquet	
	October 24, Wed.	
9:00	Report session 2 Chair: Dr. Richard Wood	Mr. Chao Lu Mr.Wei Zheng
10:20	Session 3 Nuclear fuel and material Chair: Prof. Hidekazu Yoshikawa	Prof. Yitung Chen Dr. Patricia Paviet-Hartmann Prof. Lin Shao
12:20	Lunch break	
13:30	Report session 3 Chair: Prof. Hidekazu Yoshikawa	Dr. Hai Zeng
14:20	Reliability evaluation of digital I&C system (II) Chair: Dr. Jan-Erik Holmberg	Prof. Hidekazu Yoshikawa Prof. Morten Lind Prof. Takeshi Matsuoka Prof. Ming Yang
18:00	Dinner	

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Table 2 List of workshop organizers, invited speakers and their affiliations

Name	Affiliation with its acronym	Country
Prof. Zhijian Zhang	Harbin Engineering University (HEU) Chair of the workshop	China
Prof. Ming Yang	Harbin Engineering University (HEU) Program secretary	China
Prof. Puzhen Gao	Harbin Engineering University (HEU) Logistic secretary	China
Dr. Richard Wood	Oak Ridge National Laboratory (ORNL)	U.S.A.
Mr. Koji Ito	Mitsubishi Heavy Industries, Ltd. (MHI)	Japan
Prof. Jin Jiang	The University of Western Ontario	Canada
Prof. Zhizhong Li	Tsinghua University	China
Dr. He Wang	Harbin Engineering University (HEU)	China
Dr. Man Cheol Kim	Korea Atomic Energy Research Institute (KAERI)	Korea
Mr. Nguyen Thuy	Electricite de France (EdF)	France
Dr. Jan-Erik Holmberg	Technical Research Centre of Finland (VTT)	Finland
Mr. Chao Lu	China Nuclear Power Engineering Company Ltd. (CNPEC)	China
Mr.Wei Zheng	Jiangsu Nuclear Power Corporation (JNPC)	China
Prof. Yitung Chen	University of Nevada Las Vegas	U.S.A.
Dr. Patria Paviet-Hartmann	Idaho National Laboratory (INL)	U.S.A.
Prof. Lin Shao	Texas A&M University	U.S.A.
Dr. Hai Zeng	State Nuclear Power Technology Corporation (SNPTC)	China
Prof. Hidekazu Yoshikawa	Kyoto University/ Harbin Engineering University (HEU)	Japan /China
Prof. Morten Lind	Technical University of Denmark (DTU)/ Harbin Engineering University (HEU)	Denmark /China
Prof. Takeshi Matsuoka	Utsunomiya University/ Harbin Engineering University (HEU)	Japan /China

Figure 1 shows the group photo of all participants in front of the College of Nuclear Science and Technology at Harbin Engineering University.

Fig.1 Group photo of all participants.

3 Risk and reliability evaluation of nuclear power system

The summaries of all the papers in this category are given in this chapter, by further classifying into two subjects of: (i) Reliability evaluation of digital I&C system, and (ii) Modeling and evaluation of complex dynamical system and the practical plant application

3.1 Reliability evaluation of digital I&C system

3.1.1 Software reliability analysis in probabilistic risk analysis

Dr. Jan-Erik Holmberg (Technical research center of Finland) presented an overview of the state-of-the-art in software reliability analysis in PRA, together with the introduction of two on-going international activities. They are: (i) the task group DIGREL of the OECD/NEA CSNI Working Group on Risk Assessment (WGRisk) on the taxonomy of failure modes of digital components, and (ii) the EU project HARMONICS (Harmonized Assessment of Reliability of Modern Nuclear I&C Software).

Dr. Jan-Erik emphasized the need to quantitatively assess the reliability of the digital systems in a justifiable manner in order to assess the risk of nuclear power plant operation and also to determine the risk impact of digital systems. The Probabilistic Risk Analysis (PRA) is a potent tool which can reveal, in general, shortcomings of the NPP design. However, PRA analysts have not had sufficient guiding principles in modeling particular digital components malfunctions. Currently, digital I&C systems are mostly analyzed simply and conventionally in PRA. The software reliability estimates are engineering judgments which often lack a proper justification. The use of probabilities for software reliability is based on some common understanding rather than a proper reference. The background and significance of this probability value is however not properly clarified.

The aim of DIGREL is to develop the best practice guidelines on failure modes for the reliability assessment of digital I&C systems for PRAs. In the DIGREL task group the taxonomy will be developed jointly by PRA and I&C experts. An activity focused on the development of a common taxonomy of failure modes is seen as an important step towards standardized digital I&C reliability assessment techniques in PRA. The needs of PRA guide the work, meaning, for instance that I&C system and its failures are studied from their functional point of view. The taxonomy will be the basis of failure modeling and quantification efforts. It will also help define a structure for data collection and to review PRA studies.

Contrary to DIGREL, HARMONICS tackles the problem of software reliability quantification using analytical and Bayesian approaches that take into consideration all the information available, in particular the evidence obtained by verification and validation (V&V). Key to these approaches is how different pieces of evidence are interpreted in a probability model context and how their interrelationships are assessed. This can be combined with other approaches that model the development process and use development fault data to estimate the number of residual faults.
More detail regarding this issue is described in Dr. Holmberg's paper [1].

3.1.2 Reliability analysis of digital I&C systems

Dr. Man Cheol Kim (Korea Atomic Energy Research Institute) presented on-going research activities performed at KAERI on software reliability and fault coverage as the two critical factors in probabilistic safety assessment (PSA) of digital instrumentation and control (I&C) systems in nuclear power plants (NPPs).

According to Dr. Kim, software reliability is important because software failures usually are considered one form of common cause failures (CCFs) in digital I&C system. On a similar note, fault coverage is also important because it is the measure to estimate the effectiveness of self-diagnosis features of digital I&C systems which prevents the failures of digital I&C systems from various components including CCFs.
An integrated approach combining various methods and data has been developed at KAERI for the purpose of estimating software reliability of a digital I&C system, wherein software for reliability estimation, reliability growth models, Bayesian belief network (BBN)-based methods, and test-based methods are combined with the consideration of the software development process. Various data related to not only the software itself but also the development process of the software are also taken into consideration in the integrated approach for better estimation of the software reliability. Various international cooperative activities are going on to develop a consensus method for software reliability estimation.
A method of estimating the fault coverage of a digital I&C system has been also made based on fault injection experiments. After comparing the advantage and weakness of various fault injection experimental methods, the software that implements fault injection experiments with run-time fault injection was selected as the most suitable. By applying the method to an actual digital I&C system, not only the feasibility of the proposed method were demonstrated but also several issues were identified that need to be solved further.

More detail on this issue is described in Dr. Kim's paper [2].

3.1.3 Overcoming regulatory differences regarding digital I&C

Mr. Nguyen Thuy (Electricite de France) discussed the problem of regulatory differences in different countries for digital I&C systems from the aspect of globalization of nuclear power plant technologies.

In the past, a plant and its I&C design was usually presented to only one regulatory body of a country. However, with globalization by international market of nuclear power plants, this has become no longer true: plant designers now present their designs in multiple countries. Owing to lack of international harmony of regulatory bodies however, designs accepted by one country have been rejected by another. This is problematic for several reasons. First, this raises doubts in the general public as to the questions of “Who is right? Is it really safe?” Second, this increases the regulatory uncertainty leading to increased costs and delays.

Regarding digital I&C, there are many reasons for such disharmony to occur. In particular, due to the complexity of the digital system, it is generally impossible to fully guarantee that a digital design including software is devoid of design flaws. Additionally, owing to the deterministic nature of software, digital systems are susceptible to common-cause failure that could curtail redundancy and defense-in-depth.

International regulatory bodies have made several attempts for international harmonization of nuclear regulation. However, past efforts have lead to limited results. Current efforts like MDEP (Multinational Design Evaluation Program) and WENRA (Western Europe Nuclear Regulation Association) might be more fruitful, but progress is slow and unlikely to provide practical solutions.

To complement regulatory efforts, the industry needs to do its part. Both the regulatory bodies and industries should work together to propose overall I&C architectures principles that are acceptable to all or most regulatory bodies. If no reasonable architecture can be found, it should highlight the regulatory differences that are the most cumbersome. These should be the priority targets of regulatory harmonization efforts.

Concerning the licensing of individual I&C systems, efforts might be focused on ensuring that the same design is acceptable in all or most countries, albeit a given country has specific requirements regarding verification and validation not directly affecting the design. Towards this direction, the world is divided into two sides: the first applies the IEC standards directed by requirement principle established by IAEA, and the second applies the IEEE standards to meet with the requirements and guidelines by NRC. These two sets of standards are however difficult to compare and harmonize. Therefore, "dual logo" standards of IEC and IEEE have been proposed. Nevertheless, very few of these standards have reached the final publication stage, in large part due to rivalry between the two sides. Thus, novel approaches will be needed where no side would appear to be a winner or a loser. For example, the HARMONICS project specifically aims at providing innovative software verification and justification methods that could support regulatory, industry and standards efforts.

3.1.4 RAVONSICS overview – Reliability and V & V of nuclear safety I&C software

Mr. Hai Zeng (State Nuclear Power Technology Corporation) started his presentation on RAVONSICS project by stating that safety justification, reliability assessment and verification of software in digital I&C is a difficult issue in common for utilities, vendors and regulatory body. A new international cooperation has started in this year between the HARMONICS project by 5 nuclear organizations in EU and the RAVONSICS project supported by CAEA for 6 participating institutions in China, in order to eliminate technical gap between EU and China in nuclear safety critical software safety and reliability evaluation and assessment. This, in particular encompasses, the methodologies, tools and technical standards for nuclear reliability evaluation and assessment.

According to Dr. Zeng, the main targets of RAVONSICS project are: (i) application specific software, (ii) standard elementary functions, and (iii) operating systems, with the related research topics being (i) Petri net, (ii) Bayesian network, (iii) Reliability growth model, (iv) Multilevel flow model, (iv) NUREG6010, BNL-94049-210, NUREG0019, *etc.* It is meant to verify test equipments, development tools, verification tools and system software on hardware platform as the center of case study.

3.2 Modeling and evaluation of complex dynamical system and the practical plant application

3.2.1 The Role of functional modeling in the design and evaluation of complex control systems

Dr. Morten Lind (Technical University of Denmark /Harbin Engineering University) gave comprehensive lecture on functional modeling of complex control systems and the on-going results of his research group.

Information about systems' goals and functions play a pivotal role in the design and evaluation of complex technical systems. Modern industrial systems and technical infrastructures typically include myriad of technologies. Power generation plants like NPPs include both physical components and subsystems for generation, transformation and conversion between diverse forms of energy. Further, subsystems including processing of material flows are provided to support the energy processes. The control systems play a significant role in establishing and maintaining proper operating conditions for the physical material and energy processes. The functions of the control system serve purposes of the process, albeit they rely on sensors and actuators and on information and communication technology for their realization.

Major challenges in the design, assessment and operation of such complex plants are to manage functional requirements (information about goals and functions) and their relations across subsystem boundaries. Another related challenge is the evaluation of the causes and consequences of failures. Functional modeling techniques like Multilevel Flow Modeling (MFM) provide concepts and methods to cope with these challenges. The main idea of MFM is to apply multiple levels of means-end and part-whole abstractions in the representation of complex energy and material processing systems. MFM can represent goals and functions of nuclear and conventional power plants and chemical processes and can used for integrated process and control systems, risk assessment and decision support system (alarm handling). MFM support formalized reasoning, and tools are currently being developed both in Denmark (DTU) and in China (HEU).

Prof. Lind reviewed the current status of MFM development with a particular focus on the modeling of control functions in MFM and the associated research challenges. Recent studies have demonstrated that the MFM can be used to represent complex control functions including mode changes during start-up, for instance. Ongoing work develops methods for reasoning about control which may be used for root cause and consequence analysis.

His presentation also included experiences from a project recently undertaken by the author and his group at DTU for a major Danish power utility on model based design of automation systems for distributed power generation systems. A consideration in this project was how to manage the complexity of requirements to different subsystems (including power equipment, instrumentation and computer and network hardware and software), and to be able to assess the vulnerability/reliability of the integrated system to various types of failure, especially the consequences for control functions of failures in a distributed communication network. Thus, the possible role of functional modeling concepts was investigated and a framework for model-based system design and evaluation was proposed.

Concerning the introduction of MFM and the basic principle of control function in MFM refer to Refs. [3] and [4], respectively, in the past issues of IJNS. A practical example of applying the basic principle of control function in MFM for the modeling of operating modes of a Japanese Fast Breeder Reactor is also given in this issue [5].

3.2.2 Availability analysis of nuclear power plant system with the consideration of logical loop structures

Prof. Takeshi Matsuoka (Utsunomiya University/ Harbin Engineering University) presented how the capability of his developed system safety analysis method called GO-FLOW [6-7] would be extended to treat the systems with feedback loop structure.

Nuclear power plants have logical loop structures in their system configuration. A typical example is a power source system, that is, a nuclear plant generates electricity and it is used for the operation of pumps which supply water to reactor core for the production of steam and electricity. Without an external power supply, a nuclear power plant can continue its operation. Another example is a component cooling water system. Without the cooling water, main components cannot continue their operation and generation of electricity has to be ceased. Cooling water is supplied by pumps which are driven by electricity. Supply of lubricating oil is also in the same situation.

For the evaluation of availability or reliability of nuclear power plants, it is necessary to treat accurately these logical loop structures in the analysis. Approximate methods or simply omitting method are used in many past analyses. Prof. Matsuoka proposed an accurate method for solving logical loop structure in reliability analysis, and presented a generalized method, where the concepts of “Support gap” and “Takeover” phenomenon are introduced in the generalized method. A nuclear power plant system is taken up and essential parts of logical loop structures are modeled into relatively simple form. The model has been analyzed by the proposed generalized method. Numerical calculation of the availability of this nuclear power plant model is also performed by Monte Carlo simulation method. The comparison of the analysis results by these two methods shows the adequacy of both methods.

The analysis result of nuclear power plant model shows an important role of loop structures for maintaining the overall system availability. For the evaluation of the safety of nuclear power plants, it is necessary to accurately evaluate loop structures. The analysis procedure is also useful in effectively designing high reliable systems.

More detail on this issue is described in Matsuoka’s paper [8].

3.2.3 Reliability Analysis by Multilevel FlowModels

Prof. Ming Yang (Harbin Engineering University) introduced some research works at Harbin Engineering University on developing a new reliability analysis method and a comprehensive fault diagnosis technology based on Multilevel Flow Models (MFM).

A fundamental method for reliability analysis by utilizing the MFM hierarchical flow structure is firstly introduced. The algorithms for calculating the reliability of a system with two states and multiple-states are then presented. A method for solving dynamic reliability problems by mapping MFMs into GO-FLOW models is also given.

For the qualitative reliability analysis, a Failure Mode and Effect Analysis (FMEA) method based on MFM is proposed, which can be used for analyzing the causes of the functional faults and their effects along MFM flow structures using conservation principles. On the basis of FMEA, a fault tree generation method for two-state system is proposed by mapping MFM elements into mini-fault trees, selecting a top event, connecting the relevant mini fault trees and breaking the logic loops. By this way, the reliability indexes including the minimal cut sets, element importance and sensitivity can be qualitatively analyzed. Finally, the aforementioned methodologies have been applied to develop operator support system and risk monitor for nuclear power plant.

3.2.4 Research on On-line Risk Monitor in Nuclear

Dr. He Wang (Harbin Engineering University) presented his on-going development project titled as “On-Line Risk Monitoring System (OLRMS) for nuclear power plant”.

Through on-line accessing of digital instrument and control system of NPP, OLRMS obtain the configuration information of NPP and update the online risk models and the reliability parameters of the equipment in time. Then the instantaneous risk, the cumulative risk of NPP as well as other risk information like event importance, AOT of device are calculated. By supplying such information, OLRMS can help the operator and manager of NPP to undertake decision-making process during nuclear power plant operation, maintenance and management.

OLRMS include five parts. They are: online condition monitoring unit, online updating database of reliability parameters, online updating risk model, online risk models calculating engine and the man-machine interface.

After describing the character of OLRMS, Dr. Wang described the similarities and differences between offline risk monitoring and online risk monitoring with the inter-comparison between the both risk monitoring. He then described the functions of each part of OLRMS in detail. Finally, the challenges during the development of OLRMS were discussed.

4 Advances in digital I&C and HMIT

The summaries of all the papers in this category are given in this chapter, by further classifying into two subjects of: (i) New research subjects, (ii) Relevant technical standards and human factors rating method, and (iii) Plant HMI design and evaluation.

4.1 New research subjects

4.1.1 Instrumentation and controls technology research under U.S. Department of Energy Nuclear Power Programs

Dr. Richard Woods (Oak Ridge National Laboratory) made a comprehensive overview on I&C technology research program under the sponsorship of US DOE.

Instrumentation, controls, and human-machine interfaces are essential enabling technologies that strongly influence nuclear power plant performance and operational costs. The nuclear power industry is currently engaged in a transition from traditional analog-based instrumentation, controls, and human-machine interface (ICHMI) systems to implementations employing digital technologies. This transition has primarily occurred in an *ad hoc* fashion through individual system upgrades at existing plants and has been constrained by licenseability concerns.

Although the recent progress in constructing new plants has spurred design of more fully digital plant-wide ICHMI systems, the experience base in the nuclear power application domain is limited. Additionally, development of advanced reactor concepts such as Generation IV designs and small modular reactors (SMRs), introduces different plant conditions (*e.g.*, higher temperatures, different coolants, *etc.*) and unique plant configurations (*e.g.*, multi-unit plants with shared systems, balance of plant architectures with reconfigurable co-generation options) that increase the need for enhanced ICHMI capabilities to fully achieve industry goals related to economic competitiveness, safety and reliability, sustainability, and proliferation resistance and physical protection. As a result, significant challenges remain to be addressed to enable the nuclear power industry to complete the transition to safe and comprehensive use of modern ICHMI technology. The U.S. Department of Energy has recognized that ICHMI research, development, and demonstration (RD&D) is needed to resolve the technical challenges that may compromise
the effective and efficient utilization of modern ICHMI technology and consequently prevent realization of the benefits offered by the enhanced capabilities that digital technology can provide. Consequently, several DOE programs have substantial ICHMI RD&D elements to their respective research portfolio. The objectives that can be achieved through execution of the defined RD&D are to provide optimal technical solutions to critical ICHMI issues, resolve technology gaps arising from the unique measurement and control characteristics of advanced reactor concepts, provide demonstration of needed technologies and methodologies in the nuclear power application domain, mature emerging technologies to facilitate commercialization, and establish necessary technical evidence and application experience to enable timely and predictable licensing.

Dr. Wood's presentation discussed on the ICHMI RD&D being conducted under key DOE nuclear power programs, in particular (i) Light Water Reactor Sustainability (LWRS), (ii)Advanced SMR (SMR R&D), and (iii) Nuclear Energy Enabling Technologies (NEET) programs. Those programs have dedicated research pathways to address ICHMI issues. The pathways are Advanced Instrumentation, Information, and Control (II&C) Systems Technologies for the LWRS program, ICHMI for the SMR R&D program, and Advanced Sensor and Instrumentation (ASI) for the NEET program.

The details of the SMR R&D program which Dr. Wood has been directly involved are described in Ref. [9] of this issue.

4.1.2 Wireless sensor networks for nuclear power plant applications

Prof. Jin Jiang (The University of Western Ontario) presented application of wireless sensor network (WSN) for nuclear power plant.

The WSN consists of interconnected low-powered wireless-enabled measurement devices, known as sensor nodes. Each node is composed of sensor(s) for measuring specific physical system variable(s), a microprocessor, memory and wireless communication module. The sensor nodes can wirelessly forward these data to a central receiver, known as the base station. Data gathered at the base station can be further processed. Even though the capability of an individual sensor node is limited, a sensor network is able to perform complex tasks through the collaborative efforts of a large number of sensor nodes that are strategically deployed throughout the sensing environment. For example, a sensor network can be used for measuring humidity or smog level of a certain region, for tracking certain objects of interest, as well as for monitoring the habitats, the battlefields, human health conditions or nuclear radiation levels in nuclear facilities. Owing to their ability to provide fine-grained monitoring services through the deployment of a large number of sensor nodes to form an invisible network, WSNs have been investigated for several industrial applications such as process measurement, condition monitoring, predictive maintenance, personnel management, and for plant safety system. Other applications of WSNs that have been investigated include remote diagnostics, safety shutdown, post-accident monitoring, and implementation of safety-related interlocking features.

Industry operators are very enthusiastic about WSN system as it can offer significant benefits to the effective plant operation, maintenance and monitoring. A recent survey by ON World Corporation in 105 industries reveals that over half of them already have plans to deploy WSNs in their industries. The motivations behind using industrial WSNs are convenience and cost reduction as WSNs require no wiring and are easy to install, which can take up 90% of the device cost. To address concerns with WSNs in industrial environments, several international standards have been developed recently for industrial WSNs, including ZigBee, WirelessHART, and ISA 100. It is generally expected that WSNs will gradually replace some existing wired and/or manual inspection-based approaches, as WSNs can provide a more consistent and non-intrusive way to gather data from a specific piece of equipment or an environment in a cost-effective mean. Industries that can be classified as extremely “safety-critical”, such as nuclear power plants (NPPs), are also showing tremendous interest in the use of WSNs recently. Specific applications of interest include radiation levels and dose monitoring, and equipment condition monitoring.

NPPs particularly incorporating WSNs as a wired alternative can be both inconvenient, and significantly more expensive, considering the increased safety and regulatory requirements by these industries. A study on NPPs reported that the cables, carrying safety signals, can cost over $2000/ft over the lifetime of a plant. Wires are also difficult to install, especially in existing and/or refurbished NPPs, which are more in need of additional monitoring due to equipment aging. Furthermore, the deployment of WSNs in NPPs faces unique challenges. The major concerns include: (i) the electromagnetic compatibility (EMC) between the wireless nodes and the existing instrumentation and control (I&C) and safety-related protection systems (*e.g.,* nuclear criticality and airborne contamination systems, flux detectors), (ii) the performance of WSNs in the presence of high levels of electromagnetic interference (EMI) from high power devices (*e.g.,* motors and pumps, ionizing radiation), and (iii) the performance of WSNs when deployed in such a harsh industrial layout with complex and cramped geometrics (*e.g.,* packed with cable trays, piping, valves, pumps, motors, concrete and steel structures). Realizing the potential benefits that a WSN can offer in a NPP, research initiatives have been undertaken by several groups and organizations to explore appropriate WSN deployment strategies, addressing all these concerns. Several experimental WSNs have been deployed in certain existing NPPs, in particular, for equipment condition monitoring and radiation dose monitoring. In this talk, the current state of WSNs in NPPs is surveyed.

4.2 Relevant technical standards and human factors rating method

4.2.1 A review on developing industrial standard to introduce digital computer for nuclear I&C+HMIT in Japan

Prof. Hidekazu Yoshikawa (Professor Emeritus at Kyoto University) presented a comprehensive overview on developing industrial standards to introduce digital computer for nuclear I&C+HMIT, based on his experience for the tenure period of 2002 to 2011 working as a member of Nuclear Standards Committee of the Japan Electric Association (JEA).

The I&C systems employed in the nuclear power stations in early days of 1970s had been made up entirely of analogue techniques all around the world. However, with the rapid progress of various digital technologies from 1980s, introduction of digital computers had been gradually expanded into the nuclear I&C systems until the first realization of full digital I&C systems with computerized main control rooms in 1990s for Advanced Boiling Water Reactors (ABWR) by Tokyo Electric Power Company (TEPCO)'s Kashiwazaki-Kariha Nuclear Power Station. Nowadays advanced Information Communication Technologies (ICTs) have been changing the daily work environment in nuclear powers stations both for operation and maintenance.

The review by Prof. Yoshikawa comprised three parts: (i) basic principles of nuclear safety for nuclear I&C+HMIT with touching on two difficult issues in nuclear safety, *i.e.*, common cause failure and human errors, (ii) the introduction of technical standard setup activities at the JEA, and (iii) condensed summaries of the JEA's codes and guides for HF design and software reliability of digital I&C+HMIT which have been widely utilized in commercial nuclear power plants (both PWR and BWR) in Japan. Toward the end of his presentation, he discussed briefly on the consequence of Fukushima Daiichi accident in March 2011 to the revision of those industrial standards now under discussion in Japan.

In conjunction with his presentation, refer to a paper published in IJNS on JEA guide on human factors design for computerized main control room [10].

4.2.2 The role of task complexity in the execution of computerized procedure tasks

Prof. Zhizhong Li (Tsinghua University) proposed a new method of rating task complexity to be used in the design evaluation of human-machine interface.

According to Prof. Li, the tasks to be performed by the operators in these systems are mainly cognitive. This brings great challenge in human performance prediction and human reliability analysis (HRA). Although task complexity has been proposed as a performance shaping factor in some HRA methods, it may play a more important role in the performance of cognitive tasks.

After reviewing existing models and definitions of task complexity, Prof. Li proposed a ten-dimension structure for the concept of task complexity. For the dimension of action complexity, an "operationalized" definition is given along with its measurement method based on the human information processing model and resource theory. The validity of this measure is examined by using data collected from a computerized emergency procedure experiment and compared with other measures. An experiment was designed with 15 levels of task complexity and five levels of time pressure to establish prediction models of operation time and error rate. The regression results indicate very good prediction validity of operation time and fairly good prediction validity of error rate from task complexity. The prediction models of error rate vary significantly with time pressure.

4.3 Plant HMI design and evaluation

4.3.1 Human factors engineering design process of the US-APWR

Mr. Koji Ito (Mitsubishi Heavy Industries, Ltd.) presented how the human factors engineering design method developed in Japan will be adapted to that of US-APWR plant.

According to Mr. Ito, the fully computerized Human Systems Interface (HSI) system and digitalized Instrumentation and Control (I&C) System of Mitsubishi Heavy Industries, Ltd. (MHI) has been developed in Japan, and is currently being applied to the latest Japanese PWR plant and to nuclear power plant I&C modernization program in Japan. [11] Conventional hard controls are limited to system level manual actions and a Diverse Actuation System (DAS). The computerized HSIS and digital I&C system has been applied to many safety and non-safety system applications including full I&C system for new plant and digital upgrading for current plants in Japanese Pressurizer Water Reactor (PWR) plants.

The digital I&C system can ensure defense-in-depth and diversity for plant safety and control which feature also achieves countermeasure against software common cause failures. The design including computer based procedures and alarm prioritization, relying principally on an HSIS with soft controls, console-based video display units and a large, heads up, overview display panel are to be applied to the US-APWR, a four loop evolutionary pressurized water reactor with a four train active safety system, which is currently under Design Certification Review by the U.S. Nuclear Regulatory Commission, and similar HSI design are to be proposed to European potential utilities as a part of EU-APWR's designing.

He mentioned on the computerized HSIS of the US-APWR design, the Verification and Validation (V&V) program data collection and analysis, and the study results related to the ongoing discussion of the impacts of digital systems on human performance, such as workload, navigation, situation awareness, operator training and licensing. He focused on the application of the latest human factors engineering (HFE) design process to different countries that have their own historical and well-established safety operating culture. Especially, findings and closing process of human factors discrepancies (HEDs) are important through the HFE/HSI design. Gaps between the HFE design process and plant design/licensing process were also discussed.

4.3.2 Keep the uniformity between Full Scope Simulator (FSS) and full-digital power station control room to enhance a safe operating ability of operator

Mr. Wei Zheng (Jiangsu Nuclear Power Corporation) presented his company's experience of introducing full-digitalized Russian-type PWR with the full scope simulator issue for operator training.

The Units 1 and 2 in Tianwan Nuclear Power Station（TNPS）of Jiangsu Nuclear Power Corporation (CNNC JNPC) are the first nuclear power units using full-digital instrument and control system (DCS). The unit 1 has been operating for 5 years, and the benefit of economy and society is great.Full-digital instrument and control system is very important feature of design about TNPS Units 1 and 2, and this DCS system ensures safely and stably long-term operating of TNPS Units 1 and 2.

Full scope simulator (FSS) of TNPS Units 1 and2 contain three kinds of emulation mode, such as stimulation, emulation and simulation, to ensure furthest reality of simulator, and the convenient conversion from DCS of unit to DCS of FSS come to realization.

Mr. Wei Zheng stressed on maintaining the uniformity between FSS and control room of Units 1and 2 to continually follow the modification and change of unit so that it could ensure the high reality of FSS and validity of simulator training of operator. He concluded that the safely operating ability of operator is enhanced, which will persevere for long lifetime of Units 1 and 2.

4.3.3 Nuclear I&C design and V&V engineering laboratory at CNPDC/ICD

Mr. Chao Lu (China Nuclear Power Engineering Company) introduced the "Nuclear I&C Design and V&V Engineering Laboratory which was constructed at CNPEC in July 23, 2010 by the authorization of National Energy Administration of China. This is an experimental center which has six laboratories for the construction and technical development of nuclear power plants. Among the six laboratories, both the digital I&C synthesis V&V laboratory and human engineering laboratory are the first large-scale simulator laboratories in China for the V&V of advanced main control room and the related man-machine interface systems. Both laboratories have been engaged in the V&V of the related designing and various human engineering studies for CPR1000 as well as in operator training and international information exchange.

5 Nuclear fuels and materials

5.1 Atomic scale details of grain boundary defect trapping and defect annihilation in Fe: Towards development of radiation tolerant

nano-grained metals as fuel cladding

Prof. Lin Shao (Texas A&M University) presented microscopic experimental research on developing radiation-resistant cladding material for nuclear fuel.

Understanding radiation responses of Fe-based metals is seen as essential to develop radiation-tolerant steels for longer and safer life cycles in harsh reactor environments involving particle irradiation. Nano-grained metals have been explored as self-healing materials due to point-defect recombination at grain boundaries. The fundamental defect-boundary interactions, however, are not yet well understood. Prof. Lin has discovered that the interactions are always mediated by formation and annealing of chain-like defects, which consist of alternately positioned interstitials and vacancies. Two kinds of chain-like defects: one created in bulk near boundary and other created on grain boundary are studied, and three defect annihilation models are identified. These chain-like defects are closely correlated to the patterns of defect formation energy minima on the grain boundary, which depend on specific boundary configurations. Through chain-like defects, a point defect effectively translates large distances, while only overcoming low activation energies to annihilate with its opposite. Thus, grain boundaries can act as highly efficient defect sinks that cannot saturate under extreme radiation conditions.

5.2 Corrosion and oxide layer growth modeling using deterministic and stochastic methods

Prof. Yitung Chen (University of Nevada Las Vegas) presented a detailed computational method to describe surface behavior of corrosion and oxide layer growth on the surface of steel structural material, which interfaces with special metallic flow, to be used in advanced nuclear reactors.

The issue of corrosion of structural material presents a challenge not only in lead bismuth eutectic (LBE), a potential coolant proposed for advanced nuclear reactors and accelerator driven systems (ADS), but also in the different next generation nuclear power (NGNP) systems.

To enhance corrosion resistance of stainless steels in ADS with higher working temperature, modifying the content of adding elements like chromium has been proposed. However, long testing time and huge cost of operation and maintenance of testing loops lead to scarce and scattered results of experiments, and moreover, restrain development of ADS.

Advanced computational method can help overcome the obstacle. The simulation of corrosion reaction of structural material is usually via deterministic or stochastic approach. In the deterministic approach, numerical models that include many physical and chemical factors on the microscopic scale are used.

However, inclusion of all microscopic phenomena yields a complex model, making simulation time-consuming. Moreover, the details of the boundary conditions which were obtained from costly experiments have to be provided. A stochastic approach places emphasis on the randomness of corrosion and reduces the computational cost of simulating the corrosion process.

A well-established stochastic model with proper initial conditions can yield results that are consistent with a deterministic model. A statistical and stochastic approach to study the localized corrosion was proposed in 1996.

The physical oxidation model based on a stochastic approach and simplified into a schematic two-dimensional representation can be used to study both localized corrosion and uniform corrosion. Reactions including oxidation, erosion, diffusion and transportation during corrosion was interpreted and converted into reaction of probability based on stochastic character. A few lines of code within a simulating program can generate unexpected results. 2-D theoretical approach, 2-D finite volume method, cellular automaton (CA) method, lattice Boltzmann method (LBM), and molecular dynamic (MD) method have been successfully developed. The developed analytical and numerical results have been compared with the available experimental measurements that show good agreements.

5.3 Overview of the international R&D recycling activities of the nuclear fuel cycle

Dr. Patricia Paviet-Hartmann (Idaho National Laboratory) started her presentation from the activity of INL in general to the introduction of the research activity on nuclear fuel cycle from radiochemistry which consists of the three departments of aqueous separation, pyro-processing technology, and nuclear materials characterization. She also introduced the INEL's activities not only on nuclear engineering education and training, but also the need of expanding both nuclear energy and renewable energy (wind, biomass and fuel cell) to cope with global climate challenge.

Concerning the major topic of her presentation, she first explained three fuel cycle options of (i) once-through open cycle (direct disposal), (ii) modified open cycle to reuse spent fuel treatment, and (iii) fully closed recycle. She then presented some observations related to worldwide scenario studies in the following order:

(i) Option 1: direct disposal of used nuclear fuel in U.S.A., Finland and Sweden,

(ii) Option 2: closed fuel cycle in France, Japan and UK, and

(iii) Various international R&D activities to drastically reduce the contents of high level radioactive elements to be disposed underground.

The summary of Dr. Paviet-Hartmann's presentation on the international R&D recycling activities of the nuclear fuel cycle are described in Ref. [12] of this issue.

6 Concluding remarks

The 14th International Workshop on Nuclear Safety and Simulation was held on October 23-24, 2012 at Harbin Engineering University (Harbin, China). There were eighteen papers presented by invited speakers from eight countries (Canada, China, Denmark, Finland, France, Japan, Korea, and U.S.A.), and the total number of the workshop participants was about 60 persons. The subjects of the presentations were: (i) risk and reliability evaluation of nuclear power system, (ii) advances in digital I&C and HMIT, and (iii) nuclear fuels and materials. The summaries of all presentations are compiled in this paper.

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