

APPROACHES TO PERFORMANCE BASED EVALUATIONS OF CONTROL ROOMS IN THE NUCLEAR DOMAIN



BELÉN TORRALBA



GOBIERNO
DE ESPAÑA

MINISTERIO
DE ECONOMÍA
Y COMPETITIVIDAD

Ciemat

Centro de Investigaciones
Energéticas, Medioambientales
y Tecnológicas

**APPROACHES TO PERFORMANCE BASED
EVALUATIONS OF CONTROL ROOMS IN THE NUCLEAR
DOMAIN**

BELÉN TORRALBA

Es propiedad:

EDITORIAL CIEMAT
Avda. Complutense, 40
28040-MADRID
2013

Catálogo general de publicaciones oficiales
<http://www.060.es>

Depósito Legal: M-34600-2013
ISBN: 978-84-7834-707-0
NIPO: 721-13-055-6

El CIEMAT no comparte necesariamente las opiniones y juicios expuestos en este documento,
cuya responsabilidad corresponde únicamente a los autores.

TABLE OF CONTENTS

| | |
|--------------------------------------------------------------------------------------------------------------------------------------------------|-----------|
| 1. INTRODUCTION | 1 |
| 2. SCOPE OF THE REPORT | 1 |
| 3. MAIN ACTIVITIES ON INTEGRATED SYSTEM VALIDATION OF THE OECD HALDEN REACTOR PROJECT | 1 |
| 3.1. Program Period 2003-2005: Literature review, framework for validation criteria and calibration referenced approach..... | 2 |
| 3.2. Program Period 2006-2008: Workshops with operators | 3 |
| 3.3. Program period 2009-2011: Technical workshop on ISV, criterion based approach and lessons learned..... | 4 |
| 3.4. Program period 2012-214: Model of elements for performance based control room evaluation, criterion based approach and lessons learned..... | 6 |
| 4. REGULATORY APPROACH ON HFE PROGRAM OF CONTROL ROOMS: U.S. NUCLEAR REGULATORY COMMISSION FRAMEWORK | 6 |
| 4.1. Regulatory basis of U.S. NRC | 7 |
| 4.2. Periodic update of HFE guidance of U.S. NRC | 10 |
| 5. STANDARDS, GUIDELINES AND RECOMMENDATIONS RELATED WITH HUMAN FACTORS EVALUATION OF CONTROL ROOM | 11 |
| 6. LITERATURE SEARCH | 12 |
| 7. INTEGRATED SYSTEM VALIDATION IN CONTROL ROOMS OF NUCLEAR POWER PLANTS: SUMMARY TABLES OF CASE STUDIES | 14 |
| 7.1. Case Study 1: Contextual assessment of systems usability method of VTT – Finland | 15 |
| 7.2. Case Study 2: Human factors evaluation of control room of EPR Flamanville Unit 3 – France | 27 |
| 7.3. Case Study 3: Human factors validation system and performance measures of control room of APR1400 – South Korea | 36 |
| 7.4. Case Study 4: Human factors V&V method of Tecnatom – Spain | 46 |
| 7.5. Case Study 5: TWICE integrated HSI validation of Ringhals Unit 2 – Sweden | 51 |
| 7.6. Case Study 6: Integrated system validation of control room of Oskarshamn Unit 1 – Sweden. | 56 |
| 7.7. Case Study 7: Human factors V&V of control room of Oskarshamn Unit 2 – Sweden..... | 63 |
| 7.8. Case Study 8: TIGER procedure for control rooms of Forsmark NPP – Sweden..... | 69 |
| 7.9. Case Study 9: Human factors V&V of control room of Lungmen NPP – Taiwan..... | 79 |

| | |
|---------------------------|-----------|
| 8. SUMMARY..... | 85 |
| 9. REFERENCES..... | 86 |

Acronyms

| | |
|----------|-------------------------------------------------------------|
| AAS | Alarm and Annunciator System |
| ABWR | Advanced Boiling Water Reactor |
| ANOVA | Analyses of Variance |
| AOI | Areas Of Interest |
| APR | Advanced Power Reactor |
| APS | Alarm Presentation System |
| ATHEANA | A Technique for Human Event Analysis |
| ATWS | Anticipated Transients Without Scram |
| AV | Audio/Video |
| AVT | Availability Test |
| AWARE | Westinghouse alarm system |
| BARS | Behaviorally Anchored Rating Scale |
| BOP | Balance Of Plant systems |
| COMPRO | Westinghouse computer-based procedure system |
| COP | Consortium of PLEX |
| CR | Control Room |
| CRT | Cathode Ray Tube |
| CSN | <i>Consejo de Seguridad Nuclear</i> |
| DCIS | Distributed Control and Information System |
| DCRDR | Detailed Control Room Design Reviews |
| DCS | Distributed Computer System |
| DR | Discrepancy report |
| E&D | Engineering and Design |
| ECR | Emergency Control Room |
| EPR | European Pressurized Reactor |
| EPRI | Electric Power Research Institute |
| ESF-CCS | Engineered Safety Features Component Control System |
| FAT | Factory Acceptance Test |
| FSM | Functional Situation Model |
| FSS | Full Scope Simulator |
| GE | General Electric |
| GETS | General Electric Test System |
| HAMBO | HAMMLAB BOiling Water reactor simulator |
| HED | Human Engineering Discrepancy |
| HF | Human Factors |
| HF V&V | Human Factors Verification & Validation |
| HF V&VIP | Human Factors Verification & Validation Implementation Plan |
| HFE | Human Factors Engineering |
| HFE DV | Human Factors Engineering Design Verification |
| HFE PRM | Human Factors Engineering Program Review Model |
| HFE V&V | Human Factors Engineering Verification and Validation |
| HFEITS | HFE Issue Tracking System |
| HMI | Human-Machine Interface |
| HPCF | High Pressure Core Flood System |
| HRA | Human Reliability Analysis |
| HSI | Human-System Interface |
| HUPESS | Human Performance Evaluation Support System |
| I&C | Instrumentation and Control |

| | |
|----------|--------------------------------------------------------------------------------|
| IFE | Institute for Energy Technology |
| ISV | Integrated System Validation |
| KSU | Kärnkraftsäkerhet och Utbildning AB |
| LCD | Liquid Crystal Display |
| LDP | Large Display Panel |
| LSD | Large Screen Display |
| LVD | Large Variable Display |
| MCC | Main Control Console |
| MCH | Modified Cooper-Harper scale |
| MCR | Main Control Room |
| MDRFP | Motor Driven Reactor Feedwater Pump |
| MMI | Man-Machine Interface |
| MSIV | Main Steam Isolation Valve |
| NASA TLX | NASA Task Load Index |
| NPP | Nuclear Power Plant |
| NSSS | Nuclear Steam Supply System |
| OKG | Oskarshamn Kraftgrupp |
| OKG1 | Oskarshamn NPP Unit 1 |
| OKG2 | Oskarshamn NPP Unit 2 |
| OPAS | Operator Performance Assessment System |
| PRA | Probabilistic Risk Assessment |
| PLEX | Plant Life Extension |
| PSAR | Preliminary Safety Analysis Report |
| PULS | Power Up-rate with Licensed Safety |
| PWR | Pressurized Water Reactor |
| RCS | Reactor Coolant System |
| ROCAEC | ROC's Atomic Energy Council |
| RPS | Reactor Protection System |
| RSD | Remote Shutdown Panels |
| SA | Situation Awareness |
| SACRI | Situation Awareness Control Room Inventory |
| SAT | Site Acceptance Test |
| SCRRI | Selected Control Rod Run-In |
| SG PORV | Steam Generator Power-Operated Relief Valve |
| SGTRs | Steam Generator Tube Ruptures |
| SLC | Standby Liquid Control |
| SME | Subject Matter Expert |
| SoK | Sources of Knowledge |
| SPDS | Safety Parameter Display Subsystem |
| SSC | Shift Supervisor Console |
| SSM | Swedish Radiation Safety Authority |
| TDRFP | Turbine Driven Reactor Feedwater Pump |
| TIGER | <i>Tillvägagångssätt vid specificering och Granskning av ny ERgonomidesign</i> |
| TPC | Taipower Co. |
| TSV | Task Support Verification |
| TWICE | TWO Instrumentation and Control Exchange |
| U.S. NRC | United States Nuclear Regulatory Commission |
| V&V | Verification and Validation |
| VDU | Video Display Unit |
| VTT | Technical Research Centre of Finland |

WDP
ZDP

Wide Display Panel
Zone of Proximal Development

ABSTRACT

The research program on integrated system validation contains the analysis of the state of the art on relevant research and development projects on performance-based evaluation in upgraded and computer-based control rooms in nuclear power plants.

The report analyzes practical cases (referred as case studies) to provide an overview of the methodological approaches in real application of human factors engineering in the evaluation of main control rooms of commercial nuclear power plants.

The review includes empirical studies and mainly practical industry experience. The basic literature for the review proceeded from public available documentation, such as technical conferences' proceedings and articles from scientific journals, taking into account the confidentiality of the reporting of industrial case studies on integrated system validation (implementation plans and results reports).

The case studies were analyzed with regard to twelve characteristics: study reference, domain of origin, type of study, purpose of the study, theoretical underpinning, issues of integrated system validation, validation stages, methods and measures, main results and conclusions, recommendations, further research, and references.

The state of the art report may be useful for researchers, developers, utilities, vendors, and designers of high reliability industries, who are planning to go through modernization processes or developing new control rooms, and have to test or evaluate them from a human factors' perspective.

This report shows the results of collaboration on integrated system validation between the Halden Project and CIEMAT, and the document is also issued as the Halden Project report "*Case Studies of Methodological Approaches to Performance based Evaluation of Nuclear Power Plant Control Rooms*" (HWR-1076).

1.INTRODUCTION

Technological developments are being introduced to upgrade the control rooms of the Nuclear Power Plant (NPP) industry. Advanced technology is integrated into the conventional analog-based control rooms in two ways: building advanced reactors, and as part of the modernization processes of the existing installations. The introduction of new technology and new ways of presenting process information provides new Human-System Interface (HSI) designs to support operators' tasks in the control rooms, which in turn may have an impact on the operator work, as described in the literature.

The human factors verification and validation (V&V) process of control room design includes an Integrated System Validation (ISV) activity. Further, the nuclear regulatory bodies require that new and modernized control rooms are tested by integrated system validation, i.e., testing of safe and efficient human performance of the whole operating environment (functionality).

A research program on ISV was formally established at the OECD Halden Reactor Project (named from now on the Halden Project) in the program period 2003-2005, to investigate whether new control room designs keep human performance within acceptable limits and thereby support the safe operation of nuclear power plants. The state of the art report is developed in the framework of the Halden Projects activities on ISV.

2.SCOPE OF THE REPORT

Human factors V&V activities are covered; however, the report mainly focuses on ISV. A review of the literature published on ISV projects or programs performed in the nuclear domain is presented. The report analyzes the state of the art on practical cases (i.e., case studies) in upgraded and computer-based control rooms in nuclear power plants. The main focus of the review is in the methodological aspects of the ISV projects performed, although usually the general framework of the Main Control Room (MCR) evaluation is also provided.

The scope of this work is not to compare the ISV methods and results, but instead to provide an overview of the methodological approaches followed in real application in the Human Factors Engineering (HFE) used for the evaluation of control rooms in commercial NPPs. Further, software verification and validation *per se* are excluded.

Intentionally, each case study in the report maintains the original terminology and many paragraphs of the consulted references, with the aim to preserve the arguments, descriptions and discussions of the case study, as an example, the use of human-machine interface or human-system interface or man-machine interface.

3.MAIN ACTIVITIES ON INTEGRATED SYSTEM VALIDATION OF THE OECD HALDEN REACTOR PROJECT

The ISV activities of the Halden Project are summarized in a special section of the document, instead of being presented as case studies, inasmuch as the developments, results and conclusions have been extensively reported in the Halden Working Reports (HWR) series as well as in conference proceedings. However, the main references of the Halden Projects results are provided.

The Halden Project has traditionally been involved in the design, development and evaluation of human-systems interfaces in control rooms. In 1999, Collier and Green reviewed the literature and established a knowledge base on Verification and Validation (V&V) of human factors in control rooms. The document *Verification and Validation of Human Factors Issues in Control Rooms* (HWR-598) presented a generic method for V&V of human factors, taking into account the literature review and standards and guidelines (such as NUREG-0711 and NUREG/CR-6393).

The Halden Project describes the objective of the ISV in the documents' achievements of the Halden Project programme in the 2003-2005, 2006-2008 and 2009-2011 periods. The purpose of ISV is to evaluate the safety and acceptability of new control room designs with respect to human performance. ISV concentrates on the functioning of the operating environment as a whole, and constitutes an essential step in the licensing process for newly designed or modernized NPP control rooms.

The rationale behind ISV is that the sub-components of the human-machine system are functionally integrated during operation, and that the joint effect of the total control room solution is different from the sum of the individual parts. Therefore, successful validation of isolated control room elements cannot guarantee that the integrated design solution will produce safe and acceptable human performance.

The objective is to improve the basis for establishing trustworthy decision criteria for accepting or rejecting design solutions on the basis of human performance evaluations. The performance based evaluation of control room is usually denominated ISV in the nuclear industry.

3.1.PROGRAM PERIOD 2003-2005: LITERATURE REVIEW, FRAMEWORK FOR VALIDATION CRITERIA AND CALIBRATION REFERENCED APPROACH

The main activities and results of the period 2003-2005 are related with the ISV concept based on a literature review, the framework for validation criteria and the exploration of a calibration referenced approach.

- A theoretical analysis of the ISV concept and a literature review was carried out and reported in *Integrated System Validation: Status and Research Needs* (HWR-754). Research needs for the future were identified as well as four major challenges to ISV.
 - The effort problem: amount of testing and evaluation to validate a system.
 - The generalizability problem: lack of systematic and standardized procedures that ensure representative sampling of operators and task conditions for validation.
 - The indicator problem: the performance estimators to be selected, classified, prioritized, and anchored by safety criteria.
 - The criterion problem: the decision criteria for accepting or rejecting new designs.

For the indicator problem, a taxonomy of performance measures was proposed, covering designer self-evaluation, user testing, crew performance measurement and system performance estimation. Examples of filtering mechanism were provided to guide the sampling and prioritization of human performance measures for ISV.

- A framework to support selection of relevant types of validation criteria was presented in Miberg-Skjerve and Skraaning (2004). The validation criteria should be organized in

accordance with human-centered design principles, and maintain user acceptability as a key issue throughout the validation process. The usability criteria (satisfaction-user acceptance, efficiency, effectiveness-productivity) were organized into three levels: acceptability, benefits to the operators' work process and benefits to system performance. Each of the three levels may be addressed independently or in conjunction, throughout a design process.

- A calibration referenced approach was investigated as a solution to the criterion problem, and can be seen as a complement to the requirement referenced approach. The investigation of a calibration referenced approach to validation was started in 2004, but the approach turned out to be complex, and the validity of the basis for the approach was difficult to establish (P. Ø. Braarud, personal communication, September 14, 2012). Therefore, the development of the approach was ended. The work is included in this overview of Halden Project activities since it includes some interesting ideas that could be incorporated into future work by the Halden Project or other interested parties. As described in Skraaning, Braarud and Heimdal (2004), and Braarud, Skraaning and Broberg (2005) the ideas for a calibration approach included to expose operators to calibration scenarios prior to the validation itself. During a calibration scenario, the difficulty of the task is gradually increased in order to drive the operating crew to their performance maximum, which ultimately corresponds to a condition where the plant is no longer handled safely. The variability of maximum performance scores between crews can then be used to define acceptance and rejection areas on performance scales that are employed during the validation. The calibration approach is targeted at human performance indicators that are supposed to predict the safety consequences of crew behavior across hypothetical system states that may occur during the life-time of a NPP.

The validity of the calibration scenarios in terms of giving correct calibration points for the decision criteria for acceptance or rejection of the human-machine design is one of the crucial aspects of the approach. The initial evaluation of the approach showed that establishing the validity of calibration scenarios was difficult, and hard to defend analytically (P. Ø. Braarud, personal communication, September 14, 2012). The calibration scenarios need to be different from the validation scenarios and the scenario dimensions of the human-machine design must be designed such that they do not bias the calibration point. The task difficulty (or scenario difficulty) is determined in terms of the plant process. Also, the calibration procedure will have to comply with ethical standards for studies involving human subjects. This aspect is of special importance since the control room operators may oppose to the calibration procedure, since at least one calibration scenario represents a breakdown of human performance.

One pilot test in HAMMLAB with one crew was performed in 2005 (Braarud, Skraaning and Broberg, 2005). Due to the problems of establishing the validity of calibration scenarios, the project decided not to further develop the calibration referenced approach (P. Ø. Braarud, personal communication, September 14, 2012). The project instead decided to focus on the development of a Criterion Referenced Approach to establishing acceptance criteria for use in ISV.

3.2.PROGRAM PERIOD 2006-2008: WORKSHOPS WITH OPERATORS

A one day workshop on work method assessment for ISV purposes was performed in 2007, with the participation of one control room crew. During the workshop two scenarios were run in HAMMLAB as a basis for identifying and discussing work method assessment for ISV

purposes. The main question was whether it would be meaningful to identify work method issues and whether it would be possible to evaluate what are acceptable work methods in given scenarios. Can a work method meaningfully be described as a distinct element of crew performance? Can work method issues be defined and described sufficiently clearly?

The focus during the workshop was on teamwork and meta-cognition supporting task performance. Based upon the scenario analysis, an updated list of general work method dimensions and descriptions was made –such as global plant overview, crew decision model, verification of task performance, task allocation or workload management. A summary of the workshop with operators was presented in Braarud, Skraaning and Nihlwing (2007).

3.3.PROGRAM PERIOD 2009-2011: TECHNICAL WORKSHOP ON ISV, CRITERION BASED APPROACH AND LESSONS LEARNED

The main activities of the period 2009-2011 consisted on a technical workshop meeting on ISV, the initiation of a criterion based approach, as well as a lessons learned report of the Halden Project based on their participation on industry projects.

- The *Workshop Meeting on Integrated System Validation - Status of Current Approaches to ISV and R&D Needs* was held in Halden. The aims of the workshop were to get an overview of relevant approaches for integrated system validation and their status, as well as to guide the R&D on ISV at the Halden Project. Twenty-three participants from member organizations and eighteen from the Halden Project were involved. The workshop gave a good overview of the status of guidelines and technical basis for ISV and pointed to research needs. The identified research needs focused on aspects such as defining terms and concepts, guidelines and standards that needed to be developed and updated, development of performance measures, specification of acceptance criteria, and requirements for test scenarios (such as set or type of scenarios). The outcomes of the workshop were reported in HWR-939 (Braarud, Nystad, Strand, Skrånning, Bye, Hildebrandt and Massaiu, 2010).
- A major challenge in ISV is to define and select the human performance dimensions that should be assessed, and to establish trustworthy criteria for evaluating the acceptability of design solutions. Potential techniques for establishing criteria for human performance measures without the use of a benchmark referenced approach (i.e., human performance of an existing control room serves as the reference for acceptable performance of a new or modernized control room) are being investigated.

In the criterion based approach, the acceptability criteria for human performance of the new control room need to be analytically derived. The criterion based approach firstly specifies the requirements for acceptable human performance. The test results of the new control room are then compared with the derived acceptance criteria –as opposed to comparing the test results of the new control room with the results from a benchmark control room.

The techniques used to derive acceptance criteria can be task and scenario analysis, expert judgment, operator self evaluation, identification of human performance requirements from technical specifications and safety analysis. A criterion based approach will improve the accuracy and validity of ISV and will also provide specific diagnostic information on the causes of observed human performance of the tested control room.

In 2009 the Halden Project planned the first ISV experiment on Criterion Based Human Performance Measures. Braarud (P. Ø. Braarud, personal communication, September 14, 2012) states that the motivation for the development of a criterion based approach to ISV was to overcome some of the limitations of the baseline approach. One of the main challenges of the baseline approach is how to determine that the baseline performance actually represent a sufficient performance level for the modernized control room. The criterion based approach aims at establishing absolute criteria rather than just using the performance of an existing control room as the acceptance criteria. Also, the baseline approach is mainly usable for modernization projects and not new builds. A criterion based approach will apply to both modernization projects and new control room designs. The initial work was documented in the Halden White Paper “*1st ISV Experiment on Criterion-Based Human Performance Measures*” (HWHP-032). The experiment aimed to develop and test preliminary criterion based human performance measures, as well as gather empirical basis for further development of criterion based human performance measures. In the experiment, two different HAMMLAB control rooms were configured representing two clearly different levels of acceptability with the purpose of investigating whether the criterion-based human performance measures are sufficiently sensitive to differentiate between the different control rooms. The two configurations were used to test the correspondence between the results of the criterion based measures and the control room status. The set of performance measures in the experiment comprised required crew activities, self-ratings, debriefing, teamwork, observer assessment and usability assessment of the control room. Three types of validation criteria are being developed: the status of the safety functions and barriers, the work process characteristics and the support from the control room elements (HSIs, procedures or training). The data collection was completed with two crews (each consisting of one shift supervisor, one reactor operator and one turbine operator) using the HAMMLAB Boiling Water Reactor (HAMBO) simulator (Braarud, Strand, Svengren, 2010). The analysis of the experiment was started in 2011 and the reporting of the project is planned for 2013.

- The methodology applied in ISV of modernized control rooms and insights and lessons learned from ISV performed by Institute for Energy Technology (IFE)¹ in NPP industry projects (modernized control rooms) was reported in *Human Factors Integrated System Validation – Lessons Learned from NPP Modernization Projects* (HWR-986). The HWR-986 discussed the purpose of ISV, the benchmark approach and the criterion referenced approach to performance requirements and acceptance criteria, scenarios, performance measures –task performance, work practices, cognitive measures and usability–, and the analysis of ISV results. The lessons learned are towards areas of ISV where the technical basis and guidance need to be developed or improved, focusing on the identification of needed improvements rather than presenting solutions, and some issues also suggest directions for further work. Some of the needed technical basis and guidance are related with:
 - The acceptability of how control room elements support overall human performance in an integrated control room setting, i.e., has been found easier to define requirements and to observe performance at the overall outcome level than at the level of control room elements.
 - The design of the scenarios: defining the adequate level of complexity and challenge for task and team requirements’ dimensions when testing the control room; selecting

¹ IFE hosts the OECD Halden Reactor Project.

whether the scenario progression should be restricted or dynamic if the crew handles the scenario in an unexpected way.

- The performance level results for accepting the new control room. The judgment of predefined acceptance criteria with unexpected scenario handling as well as the evaluation of the overall control room acceptability when the results of the performance dimensions are not in compliance.
- The development of performance based measures for evaluating the support from control room elements. Prioritizing different types of performance dimensions. The basis for relating human performance measures to plant safety. The prioritization of task performance and usability as the main performance constructs is recommended, as well as to carefully use cognitive measures such as situation awareness. One decisive issue for the sensitivity of task measures is the scenario design.
- The procedure for the data analysis: aggregating data to an average (mean performance) and looking for the deviating cases from the performance requirements. The use of Analysis of Variance (ANOVA) and statistical significance. The ISV test and data analysis need to be performed at a sufficiently detailed task and event level in order to be indicative of specific control room issues and to cover critical tasks.

3.4.PROGRAM PERIOD 2012-214: MODEL OF ELEMENTS FOR PERFORMANCE BASED CONTROL ROOM EVALUATION, CRITERION BASED APPROACH AND LESSONS LEARNED

The Halden Project plans to develop an overall framework of the integrated system that can be used as basis for a criterion referenced validation. In principle, the framework is generic and could as well be used as a basis for improvements of the benchmark approach or other approaches to ISV. The framework will provide a foundation for establishing criteria, safety and context relevant measures to identify the overall performance, and the control room support to achieve the prescribed criteria. Thus, the framework will serve multiple purposes:

- Support the specification of performance criteria and develop relevant performance dimensions for NPP ISV. This means to look beyond the benchmark approach to performance requirements.
- Profile and systematically structure performance observations (to be compared against the criteria and/or by use of performance measures).
- Improve the ability to diagnose and discriminate effects of single tools from observations of the total performance.
- Develop a coherent set of performance indicators and measures for integrated system validation.

The results will be used as a basis for further development of the criterion referenced ISV methodology.

4.REGULATORY APPROACH ON HFE PROGRAM OF CONTROL ROOMS: U.S. NUCLEAR REGULATORY COMMISSION FRAMEWORK

A section on the regulatory perspective on HFE approach, includes Human Factors Engineering Verification and Validation (HFE V&V), is presented and provides a framework for practical development, implementation and application of the ISV methodology. The HFE of the control room is considered a life-cycle process, and the regulations are commonly based on a process-oriented safety review strategy.

Many of the reviewed case studies refer to international requirements and standards for the HFE and ISV of control rooms. The regulatory framework and basis of the U.S. Nuclear Regulatory Commission (U.S. NRC) is explained here, since the Human Factors Engineering Program Review Model (HFE PRM) of NUREG-0711 has been taken into account in all reviewed case studies. For example, in the Spanish NPPs, the regulatory body Nuclear Safety Council (*Consejo de Seguridad Nuclear* or CSN) considers it adequate to follow the methodology provided on NURG-0711 to incorporate plant design modifications in the control rooms (all Spanish NPPs, except one, are Westinghouse or General Electric designs), in spite of following the development of safety instructions by the CSN (2009, 2010a and 2010b).

4.1.REGULATORY BASIS OF U.S. NRC

The U.S. NRC documented its analyses and regulatory positions in standard review plans, regulatory guides, regulatory issue summary reports, interim guidance documents and branch technical positions (O'Hara, Gunther and Martínez-Guridi, 2010).

The regulatory basis for addressing HFE in U.S. NPPs is in the Code of Federal Regulations (CFR), licensed under 10CFR Part 50 section 34 or 10CFR Part 52 section 47. The framework for conducting safety reviews of the HFE aspects of control rooms, both in new plants and control room modifications of operating plants, are described in U.S. NRC *Standard Review Plan* (SRP), Chapter 18 (Human Factors Engineering), revision 2 (NRC, 2007). The HFE programs of applicants for construction permits, operating licenses, standard design certifications, combined operating licenses, and license amendments are evaluated. Specific guidance to support the HFE design reviews procedures for evaluating applicants' HFE programs are provided in the *HFE Program Review Model* (NUREG-0711, 2012, revision 3) and the HSIs are evaluated using the guidance contained in the *Human-System Interface Design Review Guidelines* (NUREG-0700, 2002, revision 2). Also NUREG-1764 (2007, revision 1) of *Guidance for the Review of Changes to Human Actions* is used for the review of human performance aspects of changes to human actions, especially those involving changes in the licensing basis of the plant. *Integrated System Validation: Methodology and Review Criteria* (NUREG/CR-6393) expands the HFE PRM on understanding ISV.

NUREG-0800, NUREG-0711, NUREG-0700 and NUREG/CR-6393 are briefly described in the following.

- NUREG-0800. The *Standard Review Plan*, chapter 18 of human factors engineering, NUREG-0800, was published in 1996 (rev. 0), and revised in 2004 (rev. 1) and in 2007 (rev. 2). The purpose of the safety reviews in chapter 18 was to improve safety by verifying that acceptable HFE practices and guidelines were incorporated into the plant's design. The three application areas of SRP are the review of the HFE aspects of new plants, control room modifications and modifications affecting risk-important human actions. The process is structured in twelve areas of review that are needed for successful integration of human characteristics and capabilities into NPP design, such as described in the table 1. Not all areas may be applicable to reviewing a particular applicant's or licensee's HFE program, i.e., the review guidance contained in NUREG-0800 is adapted to address specific types of HFE reviews. While a review of a new NPP will likely use all elements, a review of HSI changes of an existing plant may use a subset of the elements.

- NUREG-0711. The *HFE Program Review Model*, NUREG-0711, was published in 1994, and revised in 2002 (rev. 1), 2004 (rev. 2) and 2012 (rev. 3). The purpose is to verify that accepted HFE practices and guidelines are incorporated into the applicant’s HFE program. The review methodology of NUREG-0711 provides a basis for performing reviews that address the twelve elements of an HFE program. Each review element is divided into five sections: background (a brief explanation of the rationale and purpose of each element), objective (the review objectives of the element), applicant products and submittals (list of materials to be provided for the NRC’s review), review criteria (the acceptance criteria for the review elements), and bibliography (list of documents with detailed information about the aspects of HFE that the element addresses). The review guidance contained in NUREG-0711 is also adapted to address specific types of HFE reviews. A brief description of the twelve elements of NUREG-0711 follows in table 1.

Table 1. Objectives of the twelve elements of NUREG-0711 (revision 3)

| Element | Objective |
|----------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| HFE Program Management | Verify that the applicant has an HFE design team with responsibility, authority, placement within the organization, and composition to provide reasonable assurance that the design commitment to HFE is met. A plan should guide the team to verify that the HFE program is properly developed, executed, overseen, and documented. |
| Operating Experience Review | Verify that the applicant has identified and analyzed HFE problems and issues in previous designs which are similar to the design under review. |
| Functional Requirements Analysis and Function Allocation | Verify that the applicant has defined the plant’s safety functional requirements and that the function allocations take advantage of human strengths and avoid allocating functions that would be negatively affected by human limitations. |
| Task Analysis | Verify that the applicant’s task analysis identifies the task requirements that personnel must perform. |
| Staffing and Qualifications | Verify that the applicant has systematically analyzed the requirements for the number and qualifications of personnel. |
| Treatment of Important Human Actions | Verify that the applicant has identified important human actions and considered human-error mechanisms for important human actions in designing the HFE aspects of the plant. They should minimize the likelihood of personnel error, and help ensure that personnel can detect and recover from any errors that occur. |
| Human-System Interface Design | Evaluate the process by which HSI design requirements are developed and HSI designs are identified and refined. The applicant has appropriately translated functional and task requirements to the detailed design of HSI. |
| Procedure Development | Verify that HFE principles and guidance are applied, along with all other design requirements, to develop procedures that are technically accurate, comprehensive, explicit, easy to use, and validated. |
| Training Program Development | Verify that the applicant establishes an approach for developing personnel training that incorporates the elements of a systems approach, evaluates the knowledge and skill-requirements of personnel, coordinates the development of the training program with the other elements of the HFE design process, and implements the training consistent with human factors principles and practices. |
| Human Factors Verification and Validation | Verification and validation (V&V) evaluations comprehensively determine that the final design conforms to HFE design principles, and enables personnel to successfully and safely perform their tasks to achieve operational goals. Involves three evaluations for identifying Human Engineering Discrepancies (HEDs). HED resolution review verifies that the applicant has assessed the importance of HEDs, corrected important HEDs, and that the results are confirmed to be acceptable. The objectives of the evaluations are to verify that the applicant has performed the following activities: |

| | |
|------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| | <ul style="list-style-type: none"> • HSI Task Support Verification (HSI TSV): an evaluation to verify that the HSI supports personnel task requirements as defined by task analyses. • HFE Design Verification (HFE DV): an evaluation to verify that the HSI is designed to accommodate human capabilities and limitations as reflected in HFE guidelines. • Integrated System Validation (ISV): an evaluation using performance-based tests to determine whether an integrated system design (i.e., hardware, software, and personnel elements) meets performance requirements and acceptably supports safe operation of the plant. |
| Design Implementation | Verify that 1) the applicant’s implementation of modernized plant systems, HSIs, procedures, and training considers their effect on personnel performance and provides the necessary support to verify safe operations, and 2) the applicant’s as-built design conforms to the verified and validated design that resulted from the HFE design process. |
| Human Performance Monitoring | Verify that the applicant has prepared a human performance monitoring strategy for ensuring that no safety degradation occurs because of any changes that are made in the plant. |

In NUREG-0711, V&V is considered a test that final design requirements are met. The V&V conducted throughout the design process is being called “HSI Tests and Evaluations”. As such, they are distinguishable from V&V since they are activities whereby issues on HSI subsystem design are explored and evaluated (NRC, 2012).

- NUREG-0700. The *Human-System Interface Design Review Guidelines*, NUREG-0700, was published in 1981, and revised in 1996 (rev. 1) and in 2002 (rev. 2). The interfaces between plant personnel and plant’s systems and components are evaluated for conformance with HFE guidelines. The guidelines to perform the evaluations of NUREG-0700 review the physical and functional characteristics of HSIs. The HFE guidelines of NUREG-0700 are organized into four basic parts, which are divided into sections. Part I contains guidelines for the basic HSI elements: displays, user-interface interaction and management, and controls. Part II contains the guidelines for reviewing six systems: alarm system, group-view display system, soft control system, computer-based procedure system, computerized operator support system, and communication system. Part III provides guidelines for the review of workstations and workplaces. Part IV provides guidelines for the review of HSI support.
- NUREG/CR-6393. The *Integrated System Validation: Methodology and Review Criteria*, NUREG/CR-6393, expands the HFE PRM on understanding ISV, but is not a requirement or review guidance. NUREG/CR-6303 provides general ISV concepts, methods and performance measures for implementing ISV. The ISV methodology should address general objectives, human performance, test methodology and procedures, test participants and test conditions, HSI descriptions, performance measures, data analysis, results evaluation criteria, and use of evaluations. The methodological considerations in the implementation of ISV are related with the validation team (should be multidisciplinary and independent), the test objectives (detailed objectives should be developed), the validation test-bed (criteria addresses the characteristics of the control room), the facilities remote from the control room and test-bed verification, the plant personnel (should represent the actual personnel and consist of a representative sample of the population), the operational conditions (specifies the requirements for operational conditions sampling and the definition of scenarios), performance measurement (addresses measurement characteristics that impact the quality of the performance measure, the identification and selection of variables), test design (addresses the coupling of crews and scenarios, test procedures, training of test

conductors and participants, and the conduct of pilot studies), the data analysis and interpretation, and the validation conclusion (the statistical and logical documentation for the acceptance of the system performance, considerations of threats to different aspects of validity). The validation paradigm is based on four forms of validity (system representation, performance representation, test design and statistical). The approaches to establishing performance criteria are based on the type of comparison: requirement referenced, benchmark referenced, normative referenced and expert-judgment referenced.

4.2.PERIODIC UPDATE OF HFE GUIDANCE OF U.S. NRC

The U.S NRC is committed to the periodic update and improvement of the HFE review guidance to ensure that it remains a state of the art design evaluation tool for HFE programs and HSI designs (new and modernized plants). The NRC's Office of Nuclear Regulatory Research is developing and updating guidance with state of the art research on human performance, advances in HFE methods and tools, and new HSI technology being employed in plant and control room design. The *Standard Review Plan* (NUREG-0800), the *HFE Program Review Model* (NUREG-0711), and the *Human-System Interface Design Review Guidelines* (NUREG-0700) were last revised in 2007, 2012 and 2002, respectively. Since the last revisions, the NRC has conducted research in many areas of HFE in order to provide a technical basis on which to update the review guidance. NUREG-0711 has been the first updated.

According to O'Hara, Higgins and Fleger (2011) the steps involved in the NRC guidance development methodology consist of user needs and lessons learned analysis, technical basis and guidance development (topic characterization, technical basis development, and guidance development and documentation), peer review (Subject Matter Experts –SMEs– to evaluate their scope, comprehensiveness, technical content, technical basis, and usability), and guidance integration and document publication (the criteria are integrated into the appropriate guidance documents: NUREG-0800, NUREG-0711 or NUREG-0700).

The updates to NUREG-0711, Revision 3, have followed the general methodology of NRC for guidance development, and are based primarily on two sources of information: user needs and comments as well as NRC technical basis documents (including the standard review plan, regulatory guides, interim guidance documents, NUREGs, NUREG/CRs, and technical reports) published after NUREG-0711 (revision 2) was completed (O'Hara, Higgins and Fleger, 2012).

The technical revisions of the Human Factors V&V element of NUREG-0711 (revision 3) states that the element was revised to simplify, streamline and consolidate to eliminate redundancy on the guidance on scenario development, performance measurement, and the process by which human engineering discrepancies are evaluated (O'Hara, Higgins and Fleger, 2012; NRC, 2012).

NUREG-0711 reviews focus on applicant submittals of the implementation plans reports and the results summary reports. The reports are more precisely defined in revision 3 and the "applicant products and submittals" section of each review element was expanded to include the expected contents of the results summary reports that are the product of the applicant's activities (O'Hara, Higgins and Fleger, 2012).

Between the topics to be address for ISV evaluation in a further revision of NUREG-0711 (revision 4), O'Hara, Higgins and Fleger (2012) point that additional guidance is needed to improve the available methods in the ISV models (stepwise or equivalence models); the

participants (obtainment of representative samples of operators); the prioritization of performance and productivity measures; the relationship of performance measures to safety; the incorporation of SMEs observations into the analysis; the establishment and use of acceptance criteria; and extend the use of Probabilistic Risk Assessment (PRA) and Human Reliability Analysis (HRA) to inform acceptance criteria.

NUREG-0711 (revision 3) was published in 2012, NUREG-0700 is scheduled for publication in 2013, and a revision of Chapter 18 of NUREG-0800 will follow shortly in the end of 2013, to make it consistent with changes to the other documents and to address advances in the NRC's licensing procedures (O'Hara, Higgins and Fleger, 2012).

5. STANDARDS, GUIDELINES AND RECOMMENDATIONS RELATED WITH HUMAN FACTORS EVALUATION OF CONTROL ROOM

Standards, guidelines, handbooks or recommendations contain information on the human factors verification and validation activities. A few of recent documents on V&V considered as more relevant for being included in this report are identified in the section. The list below doesn't pretend to be exhaustive.

- EPRI (1984). *Computer-generated display system guidelines. Volume 2: Developing an evaluation plan* (EPRI NP-3701). Palo Alto, CA: EPRI.
- EPRI (2004). *Human factors guidance for control room and digital human-system interface design and modification*. Palo Alto, CA: EPRI. EPRI 1008122.
- IAEA (2010). *Integration of analog and digital instrumentation and control systems in hybrid control rooms*. IAEA Nuclear Energy Series No. NP-T-3.10. Vienna: IAEA.
- IEC (1995). *Nuclear power plants – main control room – verification and validation of design* (IEC 61771). Geneva, Switzerland: International Electrical Commission.
- IEC (2009). *Design for control rooms of nuclear power plants*. IEC 964 (1989), IEC 60964 (2009). Geneva, Switzerland: International Electrical Commission.
- IEEE (2010). *IEEE guide for the application of human factors engineering to systems, equipment, and facilities of nuclear power generating stations*. IEEE-Std-1023-2004 (R2010). The Institute of Electrical and Electronics Engineers.
- IEEE (2011). *IEEE guide to evaluation of man-machine performance in nuclear power generating station control rooms and other peripheries*. IEEE-Std-845-1999 (R2011). The Institute of Electrical and Electronics Engineers.
- ISO (2006). *Ergonomic design of control centres. Part 7: principles for the evaluation of control centres*. ISO 11064. Geneva, Switzerland: ISO.
- NRC (2004). *Human system interface design review guideline* (NUREG-0700). Rev. 0 (1981), Rev. 1 (1996), Rev. 2 (2004). Washington, D. C.: U. S. Nuclear Regulatory Commission.
- NRC (2007). *Standard review plan for the review of safety analysis reports for nuclear power plants, chapter 18. Human factors engineering* (NUREG-0800) Rev. 2 (2007). Washington, D.C.: U.S. Nuclear Regulatory Commission.
- NRC (2012). *Human factors program review model* (NUREG-0711). Rev. 0 (1994), Rev. 1 (2002), Rev. 2 (2004), Rev. 3 (2012). Washington, D. C.: U. S. Nuclear Regulatory Commission.

- O’Hara, J. (2009). *Applying human performance models to designing and evaluating nuclear power plants: review guidance and technical basis* (BNL Technical Report BNL-90676-2009). Upton, NY: Brookhaven National Laboratory.
- O’Hara, J., Stubler, W., Higgins, J. C. and Brown, W. (1997). *Integrated system validation: methodology and review criteria* (NUREG/CR-6393). Washington, D. C.: U. S. Nuclear Regulatory Commission
- O’Hara, J.M. (1994). *Advanced human-system interface design review guideline. General evaluation model, technical development, and guideline description* (Volume 1). *Evaluation procedures and guidelines for human factors engineering reviews* (Volume 2) (NUREG/CR-5908). Washington, D. C.: U. S. Nuclear Regulatory Commission.

6.LITERATURE SEARCH

The main objective of the literature analysis was to identify the methodological approaches to ISV in control rooms in high reliability organizations, specifically on commercial NPPs. The state of the art review covers both ISV approaches on modernization processes of control rooms as well as on the design of new advanced control rooms.

A variety of keywords have been used in the data searches, including combinations of human factors evaluation, verification and validation, integrated system validation, performance-based evaluation, performance measures, modernization of control room, human-system interfaces, hybrid control rooms, computer-based control rooms, main control room, control center and nuclear power plant.

The literature review included empirical studies and mainly practical industrial experience. The basic literature for the review proceeded from technical conferences proceedings and articles from scientific journals. Therefore, the limitations of this report relate with the available information in the scientific literature, taking into account the confidentiality of the industrial case studies on ISV reporting (i.e., ISV implementation plans and ISV results reports).

It is important to explain that the description of the case studies varies in level of detail and extension, mainly due to the basic public documentation available. Further some sections of the tables may not be filled in or only partial information has been included.

The methodological approaches of the nine case studies considered in this report are presented in alphabetical order, according to the nation (country) where the case studies on ISV were carried out. The countries are Finland, France, South Korea, Spain, Sweden and Taiwan. As above explained, the terminology and descriptions used in each case study has been maintained as far as possible, not making new interpretations of the results.

The case studies were analyzed with regard to twelve characteristics: study reference, domain of origin, type of study, purpose of the study, theoretical underpinning, issues of integrated system validation, validation (performance-based evaluation) stages, methods and measures, main results and conclusions, recommendations, further research, and references.

The content of the case studies for the analyses of the evaluation projects is always presented as a summary table (see table 2), consisting of:

- Study reference – the institution or the corporation to which the authors of the integrated system validation approach belong and the main object of the study.
- Domain of origin – specifies the domain in which the study originally emerged e.g., aviation, or nuclear power plant.
- Type of study – an experiment or a field study, the participants on the study (e.g., operators, or domain experts), and the period of data collection.
- Purpose of the study – specifies the main focus and objectives of the study (including research questions and hypotheses) as well as previous related studies (if any).
- Theoretical underpinning – refers to the specific theoretical basis that underlies the study. The standards and guidelines of reference are also presented.
- Issues of integrated system validation – specify what aspects of the integrated system validation were reported (e.g., approach, training, scenarios, methods, measures, performance criteria, evaluation team).
- Validation (performance-based evaluation) stages – specify the definition/concept of validation as well as the phases of the evaluation process.
- Methods and measures – indicate the participants, the scenarios, the applied methods (interviews, observations, usability questionnaire, etc.), the performance measures (e.g., detection and diagnosis, workload, situation awareness, and teamwork), the performance criteria (reference of the evaluation), and the approach for establishing the causes of performance.
- Main results and conclusions – describe the main outcomes, knowledge, and conclusions of the study.
- Recommendations – provide the suggestions and the proposals originated as a result of the study (e.g., design or methodological recommendations).
- Further research – describes whether there are proposals for additional research on the same issues, if the described study is part of an extensive project and some activities that are being carried out.
- References – complement the study reference characteristic with a list of citations of the reports related with the described study. The main references on which the elaboration of the summary table is based as well as additional references related with the study.

Table 2. Summary Table Structure

| |
|-----------------------------------------------|
| <i>Study reference</i> |
| |
| <i>Domain of origin</i> |
| |
| <i>Type of study</i> |
| |
| <i>Purpose of the study</i> |
| |
| <i>Theoretical underpinning</i> |
| |
| <i>Issues of integrated system validation</i> |
| |
| <i>Validation stages</i> |
| |
| <i>Methods and measures</i> |
| |
| <i>Main results and conclusions</i> |
| |
| <i>Recommendations</i> |
| |
| <i>Further research</i> |
| |
| <i>References</i> |
| |

7. INTEGRATED SYSTEM VALIDATION IN CONTROL ROOMS OF NUCLEAR POWER PLANTS: SUMMARY TABLES OF CASE STUDIES

The selected methodological case studies of human factors evaluation (V&V) of nuclear power plants control rooms are presented as follows:

- Contextual Assessment of Systems Usability (CASU) method of VTT (Finland).
- Human factors evaluation of European Pressurized Reactor (EPR) Flamanville Unit 3 of EDF (France).
- Human factors validation of Advanced Power Reactor APR1400 of KAIST and KEPRI (South Korea).
- Human factors V&V activities of NPPs of Tecnatom (Spain).
- Validation of Ringhals Unit 2 (TWICE project) of Westinghouse and Ringhals NPP (Sweden).
- Validation of Oskarshamn Unit 1 of IFE and Oskarshamn NPP (Sweden).

- Validation of Oskarshamn Unit 2 (PLEX project) of AREVA NP and Oskarshamn NPP (Sweden).
- TIGER procedure for human factors evaluation of Forsmark NPPs (Sweden).
- Human factors V&V of Lungmen NPP of National Tsing Hua University, General Electric and Atomic Energy Council (Taiwan).

As indicated above, the case studies described on summary tables maintain the original terminology and many original paragraphs of the consulted references, i.e., we are reproducing the author's text, and excerpts of the original report are presented. The main author's references are indicated on each summary table.

7.1.CASE STUDY 1: CONTEXTUAL ASSESSMENT OF SYSTEMS USABILITY METHOD OF VTT – FINLAND

| |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Study reference |
| VTT. Development and application of the Contextual Assessment of Systems Usability (CASU) method. |
| Domain of origin |
| Empirical studies of work in complex industrial environments, primarily in nuclear power plants, but also in domains such as ship maneuvering and anesthesia. |
| Type of study |
| Simulation and normal work situation. Operator performance using the control room. End users: Operators. Development and application of the CASU method based on a longitudinal approach labeled as "usability case". |
| Purpose of the study |
| The Technical Research Centre of Finland, VTT, started the validation approach of nuclear power plant process control systems in the nineties (with simulator studies at Barseback NPP). A more systematic development of an approach to ISV began within their national research program for nuclear safety SAFIR 2003-2006, as Finland decided to build a new NPP and also the modernization process of the control rooms of all four Finish NPP units was initiated. The methodological approach to ISV offers a modeling method to develop contextual evaluation criteria to be used in the evaluation. The CASU method has been empirically applied in several usability cases to evaluate the control room design of Finnish NPPs. VTT has developed a specific approach for the pre-validation of human system interfaces, which has been applied to several validation tasks in Finnish NPPs. Lessons learned of the pre-validation application are presented in a special section of methods and measures of this summary table. |
| Theoretical underpinning |
| <ul style="list-style-type: none"> • The theoretical bases for the ISV approach are extensively explained. The whole system of NPP process control can be described as a complex sociotechnical system that cover a large problem space, comprise possible hazards, are social in nature, are distributed, and constitute of coupled interactions (Vicente, 1999)². |

² Vicente, K. J. (1999). *Cognitive Work Analysis. Toward a Safe, Productive, and Healthy Computer-Based Work*. Mahwah, N.J.: Lawrence Erlbaum Publishers.

The activity system model of Engeström (1987)³ and the functional model of physical domain (Rasmussen, 1986⁴, Vicente, 1999⁵) are employed in the elaboration of the systems usability approach, and define the users' task in a new systemic way, called the core task. The core task demands are defined by identifying complexity, dynamicity, and uncertainty constraints of the specific domain under analysis. Human skills, knowledge and collaboration are resources to cope with them. The core task demands allow the identification of relevant scenarios to be used in the evaluations and the primary tasks on which attention should be directed in the evaluation. The core task demands are used to infer systems usability claims, the fulfillment of which can be reviewed in a longitudinal integrated system validation process.

The cultural historical theory of activity (Vygotsky 1978)⁵ distinguishes between operations, actions and activity, thus providing different levels of granularity to the analysis of work performance. The cultural historical theory of activity is taking as basis for identifying the tool functions in the control room: instrumental (the operators impact the process), psychological (affects the operators' mental structures in understanding and controlling the process) and communicative (the operators can learn about other crew members' intentions and on-going tasks while using the interface). Each of the functions of the new tool has an implication on the safe operation of a NPP and must be considered when validating it. The appropriate fulfillment of the:

- Instrumental function assumes that the system accomplish that operators are able to carry out the necessary operating and monitoring tasks. Refers to the capability of the tool to cause an aimed effect or maintain a desired outcome.
- Psychological function requires that a fluent interaction with the system can be developed and that operators' competence development is supported. Reflection of own behavior also becomes possible.
- Communicative function requires that the system must support operating crew's collaboration, communication and shared situational awareness. Addresses issues of sense-making in action and the meaning of action in a wider cultural and societal perspective.

Data collection methods and evaluation metrics have been designed to include the three functional aspects of the tool. The way the interface is actually used in a particular activity is investigated, to capture all functions of the interface in usability evaluation. Practice allows to understand the individual's or the crew's learned way of conducting the work, conceptualizing the object of work, apprehension of what is intended in the work, and insight of what is a good way of utilizing available resources and tools for the work. Practice is always socially founded and what is valued as good work is shared in the community. Tool functions are used to define systems usability claims under which the content-oriented core task demands can be ordered. A tool with high systems usability is able to fulfill all three functions in actions within an activity system. Systems usability is the comprehensive quality requirement that the control room system should fulfill in all process control situations and that should be targeted at in the design. Systems usability refers to the context and content in which the technologies under evaluation are used.

- Some referenced guidelines and standards are NUREG-0711, NUREG/CR-6393, IEC-9064 and EPRI (2004).

³ Engeström, Y. (1987). *Expansive Learning*. Jyväskylä, Orienta.

⁴ Rasmussen, J. (1986). *Information Processing and Human-Machine Interaction*. Amsterdam: North-Holland.

⁵ Vygotsky, L. S. (1978). *Mind in society: the development of higher psychological processes*. Cambridge, Massachusetts: Harvard University Press.

Issues of integrated system validation

Theoretical basis. Evaluation phases. Methods. Measures. Evaluation team. Performance criteria: benchmark, normative and expert judgment referenced approach. Pre-validation during the design process.

Validation stages

- Definition of ISV. The focus of evaluation in ISV has been defined by U.S. NRC (NUREG-0711) and Electric Power Research Institute (EPRI) (EPRI, 2004) as being holistic and focusing on the functioning of the system. VTT propose two further specifications in the concept of ISV (improve safety through usability and a longitudinal process).
 - ISV is holistic and focuses on systems. The object of the integrated validation should focus on the whole operating environment so that the sub-components of the work environment are functionally integrated during operation. The problem is how to create a holistic picture of the functionality of the system, being as only summing up singular evaluation results is not sufficient.
 - ISV focuses on functioning of the system. ISV is evaluation using different types of performance-based measures to ensure that the design is consistent with performance requirements and acceptably supports safe operation of the plant.
 - The purpose of ISV is to improve safety through usability. Human behavior may basically be considered from two points of view in design: (1) the perspective of perceiving human as a possible cause of risk in the proper and safe functioning of the system under given constraints; (2) the usability-oriented human-centered design perspective emphasizes the positive contribution of human performance for safety and productivity, considering that human operators question the operating constraints, as the reflection on the constraints creates awareness of the situation more globally. The rationale for evaluation of the HSI is not only safety but rather safety through usability.
 - ISV is a longitudinal evaluation process. ISV supports two functions: provide insights to regulatory acceptance of new technologies –normative– and receive design feedback and new ideas –innovative–. Articulation of the two functions sensitized them of the nature of interaction between the regulator (regulator-driven normative acceptance) and the utility (utility-driven innovation) in the course of the design process. The two functions interrelate and the interaction between the interest groups is much more complicated. The consequences to the method development were the identification of time and design-process-maturity related constraints. The evaluation should support systematic accumulation of knowledge and insights both with regard to design and regulatory acceptance.
- Overall evaluation process. The CASU method consists of four separate phases in the evaluation process: modeling, data collection, data analysis and assessment.
 - Modeling phase: define the process situations to be used in the tests, the situational measures and the criteria against which the measures are compared. Several kinds of models need to be developed to create the basis for the control room evaluation, such as work domain modeling, core task modeling and scenario modeling. Modeling is a process of mapping a general domain perspective to situation specific scenario perspective, and it also includes mapping of general core task demands to tasks required in specific situations.
 - Data collection phase: experimental or empirical phase of the validation process, as the data collection can be carried out either in a simulator or in a normal work situation, with the aim of gathering information about the usage of the system under evaluation. The data collection methods include observation of activity, questionnaires, interviews, direct process performance data, simulator data, behavioral data of operator performance

and video recordings. The data base comprises both quantitative and qualitative data.

- Data analysis phase: treat the gathered data in successive phases. A course of action analysis is accomplished by each test situation and, based on that description, analyze process control performance, work practices –work orientation and habits of action– and a description of the operators’ experience concerning the usability of the system (experienced appropriateness of the system). As an example, the crew’s practice of process control is checked based on both observable behavior and justifications of the crew for their actions, and the experienced appropriateness is analyzed based on the interview data.

A timeline of the process phases that take place during the operational situation is constructed to analyze the course of action. The operational and the process events are presented in chronological order. Observations, actions and communication of the operators are added.

The achieving of quantitative results of the tests is not very time consuming. The data are helpful to identify major effects on performance. As test subjects are highly experienced operators, most probably only minor performance outcome differences are identified and operators adapt well to the use of new systems. For the effects of tools, qualitative results concerning work practices are absolutely necessary. Qualitative analysis is time consuming and requires considerable domain expertise.

- Assessment phase: the analysis results are compared with the measures chosen in the modeling phase to make inferences about how well the new system fulfils the functional criteria of systems usability (instrumental, psychological and communicative). The assessment is made by combining three points of view: the process measures, the tools’ ability to promote appropriate work practices, and the interface quality.

Methods and measures

- Measures. Operator performance in using the control room system is the basis for evaluation. Three main indicator groups are used in the systems usability metrics: actual outcome of action (course and results), work practices and operator experience. Good system usability is visible in the users’ work performance because systems usability promotes the construction and development of work practices. Good work practices are oriented to the core task and produce good directly measurable results. The core task is defined by the context and objectives of the activity.

For each indicator group, different metrics are defined according to the tool function (instrumental, psychological and communicative) the system should fulfill. All indicators are contextually defined so that scenarios and tasks relate to the core task demands of the process control work. The main measures employed in analyzing the three functions are:

- Instrumental. Process control performance criteria and data related to efficiency of routines of using the system (secondary tasks).
- Psychological. Cognitive measures for evaluating the operators’ coordination with the tools and procedures, and within the crew.
- Communicative. The operators oriented to the core task demands in the process control tasks, and whether the overall significance of singular events were comprehended and shared within the crew.

The grading scale was a qualitative three level scale that expresses: (1) degrading, acceptable or developing levels of performance; (2) reactive, confirmative or interpretative practices; and (3) rejection, acceptability, or promisingness of the tool.

Data collection methods and evaluation metrics have been designed to capture each of the three functional aspects of the tool. The system usability metrics are included in table 3.

Table 3. Systems usability metrics with regard to different tool functions

| Focus of analysis Tool functions | Outcome of action | Work practices | Experience |
|-------------------------------------|------------------------------------------------------------|---------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|
| Instrumental | Task achievement, time, errors | How tools are embodied in meaningful routines | Experience of appropriate functioning, joy of achieving intended effect |
| Psychological | Cognitive constructs and measures, e.g., SA, mental models | How coordination with tools, control of own activity is accomplished | Experience of fit for human use, experience of own competence, sense of control |
| Communicative | Amount and content of interactions and communications | How usage of tools is shared within the community and how usage conveys meaning | Experience of trust in technology, experience of shared motive, experience of support for personal style |

- Methods. Individual methods developed to evaluate systems usability with CASU are described.

- Task analysis – Functional way. The basis of the evaluation for extracting the systems usability is the task analysis. The activity level is reached by conducting the task analysis from a functional perspective (i.e., functional task analysis). The task is analyzed from the point of view of the objectives of the activity –describes why users do what they do. The objectives have societal foundations and in one activity there are typically many contradictory objectives, such as maximal electricity production and minimal radiation to the environment. The functions and subfunctions that fulfill the objectives construct the hierarchical functional model of the task. In the functional task model for NPP process, on the objectives level are the objectives of the activity, on the sub-objectives level are the functional sub-objectives that fulfill the objectives, and in the system level are the systems that enable the accomplishment of the objectives.

The functional models of the work (generic and situation specific) explicate the possible reasons for action. By comparing possible reasons with those that people actually give, behavioral markers are developed to describe how people act. As a result, differences in work practices can be articulated.

The scenarios used in evaluation also need to be modeled. In Functional Situation Models (FSM), the general task model is given in a situational form. The situational events give meaning to the functions and describe the users' reason for actions.

In the model of the core task, the task is looked at from the domain perspective, and also from the individual user's perspective, for identifying the work practices with which the users cope with the functions of the domain.

The functional task analysis aims to understand the reasons for users' actions that relate to the functionality of the object, and thus define the good practices in particular domains and situations. With the aid of functional task models, the measures for the evaluation can be elicited.

- Data collection – Justification of own actions. To understand the construction of the activity with the new tool and also to know how the users take into account the functions of the domain (task model) and their situational manifestations (FSM), in addition to the usual data collection methods when evaluating an interface, interviews with the users about their interaction with the tool are carried out. In the "stimulated process tracing interviews" method, the operators recall the scenario from four points of view: (1) what happened in the process during the scenario (a process event at a time); (2) how was each event detected, allows to understand how the interface was utilized in the activity

(e.g., interface, procedure or other operators); (3) what was the impact of the event in the overall process (whether the meaning was communicated by the interface); and, 4) what actions were taken and how (to assess whether the right actions were afforded). During the “stimulated process tracing interview”, a spreadsheet is formulated, that represents the crew shared understanding of the simulator run. In the assessment phase, the table is compared to the situation models to assess the practice of the crew.

While recalling and constructing the scenario, the operators simultaneously reflect about their behavior and the reasons for it, the use of the interface in the scenario and its usefulness, the meaning of the received information, and the work practices employed to cope with the task demands.

- Measures – External and internal good practice. The systemic quality of a complex system interface can be evaluated through studying the quality of the practices. For the analysis of the context of practice, the model of an activity system and the rules to define the core task of a particular work are introduced.

Two types of performance-related evaluation dimensions analyze practices: external and internal measures. While the external measures of practice can be employed without considering the particular content of activity in the specific scenario, the establishment of internal good practices measures requires an understanding of what is a good practice in the chosen scenario. The external assessment dimension connects with the effectiveness of the artifact (tools), while the internal assessment dimension is especially relevant with regard to fitness for human use and meaningfulness of the artifact. This is, the outcome-related measures may not differentiate between different users or interfaces (task completion time) as the users are experts, but the differences are in the way of reaching the outcome (decision-making process). The advantage of internal performance measures is that conclusions about the usability can also be drawn analyzing normal activity, because inferring usability based on stable work practices through different situations.

- Assessment – Development potential of the system. The assessment of the usability of the interface is based on all data collected in the empirical phase. The models created in the first phase of the evaluation process are compared to the empirical data collected in the test situation. The result tables of operators’ stimulated interviews should resemble functional situation models, i.e., relevant information was mediated to the users and correct actions were taken.

The new interface might not be completely usable, but some features have the developmental potential to carry the whole activity to a new level. The users maintain a current work practice that has a certain Zone of Proximal Development (ZPD), which is the gap between their current level and their potential level of development. New tools with systems usability can help the users realize the ZPD, learn new practices, and thus promote the development of the whole activity system.

- Evaluation team. The evaluation group participating in the data collection of the experiments is multidisciplinary, and consists of two or three human factors specialists (run the tests and gather the data), one domain expert (on-line comment and evaluate the process control performance) and one or two simulator personnel (run the simulator and prepare process data logs).
- Reference of evaluation. The reference used in ISV is multifaceted, covering three reference approaches: benchmark, normative and expert judgment.
 - The benchmark approach with prior system is used as reference. The comparison is made on multiple levels of abstraction, such as the individual performance indicators and the whole concept of operations.
 - The normative reference approach defines the criteria for good performance that are

developed by analyzing the core task of process control in a modeling exercise, and by the model of scenario. The normative reference constitutes the frame for a longitudinal ISV process. The procedure is labeled as a “usability case” in which ideas of safety case are applied. With the aid of the tool functions, claims that apply to different core task demands (sub-claims) are created. At different times of the design process, distinct validation tasks are accomplished which provide evidence for the system. These evidences are connected to the claims with arguments that reveal whether, and to what extent, the claims are fulfilled.

- The expert judgment approach is used when the expert explains the basis of judgment of the main scenario phases (detection, mitigation, diagnosis and stabilization) and also for the use of procedures, and crew communication and cooperation.

A snapshot type validation is unable to give a realistic overview of the safety of operations, because it cannot take into account the maturity of the whole work system in the control room at that time. The issue of reference is addressed by conducting validation in a longitudinal way: validations of new systems are carried out several times during the system development to obtain evidence (or counter evidence) of safe operation.

Methods and measures of pre-validation

- Pre-validation. The pre-validation activities are distributed along the design process, being tightly connected to many other activities of the HFE process, such as training or procedure design. The pre-validation test refers to small-scale usability tests that precede the final testing of the integrated system (i.e., the ISV tests). Prototypes of the individual subsystems are evaluated through small-scale usability tests.
 - Development of the pre-validation methodology. The main requirements for pre-validation testing are: (1) Tests support the iterative design of a system. The tests should be carried out cost-effectively and quickly enough to deliver the input to the design process, but should truly assess the validity of the system. The tests should cover all the subsystems and their functionalities. (2) Timing has to be carefully planned, and testing of the system should be scheduled at the right time (i.e., when the design work has not yet been completed, and the recommended changes can be implemented).
 - Methods. The methods and techniques to the evaluation of systems usability of complex technical systems have been adapted as pre-validation methods:
 - Usability test: the usability of a technical system is improved through practical tests with users. The participants represent real users and do real tasks. The personnel who are accomplishing the test observe and record what the users do with the system, how they communicate and cooperate. Possible problems and recommendations on how to improve the system are identified.
 - Expert evaluation: the experts evaluate a HSI with a reference to a specific set of criteria, identify and rank the usability flaws according to their severity.
 - Cognitive walkthroughs: possible end-users of the system go through a sequence of actions with the tested user interface and evaluate its functionality and usability.
 - Focus groups: group discussions in which participants explain their experiences and opinions about the usage of the system. Focus groups are used in the early phases of the design to probe possible users’ attitudes and beliefs.
 - Usability questionnaire: a list of items of the system usability.The methods and techniques measure different aspects of human performance, being assumed that if a system is usable humans can perform well.
 - Measures. Performance measures are quantitative measures that give information of the outcome of human activity; practice measures give information of the core task orientedness of activity; and user experiences give information such as the

promisingness of the system for future work.

- Pre-validation test phases. The five main phases in the pre-validation of the control room (CR) HSIs are: planning, modeling, data collection, analysis and assessment.
 - a. Planning. To get familiar with the system that will be evaluated, formulate goals and constraints for the evaluation, and define the relevant methods and measures that will be used.
 - Training and familiarization. Training of participants and personnel conducting the test is carried out before testing. Designers provide training on the new concept of operations, on new features of the HSI and on modifications of operational procedures. Technical feasibility of the simulator runs is also tested beforehand. Demonstrations and simulations that are used in training are different from those that are used in actual simulator tests.
 - Defining goals and concerns. Determine the main focus of the pre-validation activities: the systems included in testing.
 - Task selection. The main task is the functional testing of HSIs in a simulator environment. Tasks and scenarios should be selected from the point of view of the systems to be tested, i.e., cover all the features of the HSIs, and select a representative set of situations. Small-scale tests of particular features of the HSIs and large-scale tests of the whole system are recommended. The task selection is carried out in collaboration with designers, process experts and usability experts.
 - b. Modeling. To develop a conceptual basis for the assessment, and understand, analyze and describe the task-specific requirements for operator activity. Tasks and scenarios for the simulator tests are modeled, i.e., are hierarchically analyzed to specify the task structure. Operating procedures can be used in the development of the hierarchical task breakdown structure. After the breakdown of the tasks, it is defined what information is presented on different display screens and other HSIs at different phases of task execution.
 - c. Data Collection.
 - The validation team consists of two or three human factors specialists who conduct the tests and gather the data. Designers will participate in the training of other participants, and will answer questions and provide additional information during the pre-validation activities. At least one simulator expert runs the simulator.
 - Participants. Two or three crews of CR operators are recruited for pre-validation testing, being preferable the selection of operators with different levels of experience.
 - Equipment and material. Before pre-validation testing, simulator models are developed in an engineering and design (E&D) simulator. Pilot tests are conducted to verify the functioning of the E&D simulator. All the material for briefings, walkthroughs, simulator tests and debriefings is prepared based on the modeling work. Before pilot testing, detailed scenario descriptions are prepared for each test. The guides include instructions for the placement of test personnel and video cameras in the simulator, actions that are carried out, measures that are used and questions that are asked.
 - Description of test activities. The activities to collect information in a pre-validation test are presented in the order they are usually conducted: (1) Observation of training sessions. The validation team gathers, during operator training sessions, comments on important usability issues that can be discussed in the interviews. (2) Expert evaluation. Usability experts evaluate the design

before simulator testing focusing on general usability issues, such as the visual layout of a user interface, the navigation and the functionality of control devices. (3) Structured interview before simulator testing. All operators who will participate in the simulator tests are interviewed beforehand, with a special emphasis on the evaluation of their knowledge and understanding of the new HSIs and/or concept of operations. (4) HSI-oriented walkthroughs. In order to evaluate the usability of the new HSIs, walkthroughs are carried out on screen paper mock-ups. Operators are asked about their positive and negative experiences with the new displays, and suggestions for improvements are gathered. They evaluate the design from the CR operator's point of view, concentrating on issues such as the possible lack of critical process information, and problems in the functional division of the system into display pages. A special emphasis can be on displays with a small role in the simulator tests. (5) Simulator testing. To test the operators' ability to understand the new HSI design and make operations with the new HSIs (concept of operations) simulator tests are carried out. Includes both small-scale simulation tests with CR operators (for testing individual functionalities) and representative realistic simulator tests. Instructions, at the beginning of the test, to the operators include a short description of the status of the process and automation system. The instructors do not provide answers to the tested operational tasks, but the operators have a possibility to try to find the solution to the questions and do the needed operations. During the implementation of the test, members of the validation team make observations, video-record the test and rate online the performance. (6) Process tracing interview. Immediately after the test a process tracing interview is carried out for clarifying the perception of the state of the process on which the operator's actions are based. The test is enacted and discussed with operators, and questions on the usability of the new design are asked. The operators describe the process events that occurred in the test run, the operations associated with particular events, the meaning of each event from a holistic process point of view, and the information or user interface element in which the detection of a particular event was based on. The questions are modified to suit each specific task. (7) Questionnaires. After the complete simulator runs, the operators complete the workload questionnaire. After all simulator tests, the operators complete a usability questionnaire providing information of the functionality and usability of the new systems. The questionnaire includes statements of the control room's instrumental function –task effectiveness–, psychological function –efficiency and suitability for the user–, and communicative function –support for shared situation awareness and cooperation–. (8) Debriefing interview. At the end of each test day, a debriefing interview is arranged with operators, designers and usability experts, with a special emphasis on the evaluation of the role of the new operating system in the operator's work.

- d. Data analysis. The data are processed in successive phases. Test data are analyzed mainly through qualitative analysis methods, but also quantitative analyses are carried out. The analysis of video data focused on operators' communications, directions of gazes, and operations and movements.
- e. Assessment. The pre-validation activities provide evidence of the validity of the concept of operations, the usability and functionality of a particular set of user interface elements and the adequacy of the training activities.
 - Evaluation of operational concept. Both observational and interviews data

provide information of the effects of HSI changes on operator practices. Aspects of operator performance that are registered: task completion (performance of the action/task), errors in performance (fault actions), fluency of performance (amount and type of repetitions, interruptions and hesitations), as well as communication and collaboration (number and content of speech acts). The interviews provide information of the operators' understanding of the concept of operations –function and meaning of the new systems–, differences between the new and old solutions, subjective experiences and preferences, situation awareness, mental workload, adequacy of the new concept of operations, and recommendations and suggestions for improvements.

An early assessment of the effects of the new HSIs on operator work practices is derived based on the qualitative and quantitative evidence.

- Evaluation of the usability of HSI components. Walkthroughs, observations and interviews provide evidence of the functionality and usability of the HSI components. (1) HSI-oriented walkthroughs inform of the main dimensions of usability (e.g., visual clarity, visibility, consistency, familiarity, flexibility and error prevention). (2) Observation of operator performance gathers information of task completion accuracy, fault actions and fluency of performance providing indirect evidence of the usability of the new design. (3) Interviews provide evidence of the operators' understanding of the use of information presentation formats, the user satisfaction with the new information presentation formats in comparison to the old design, and suggestions for improvements. Also the usability questionnaire –completed at the end of the pre-validation session– provides information of the functionality and usability of the new HSIs.

A preliminary assessment of the usability of the new design is obtained, as well as a list of possible problems and challenges with solution suggestions.

- Evaluation of operator training. Suggestions for the operator training –such as relevance, adequacy and desired volume of training– can be given and a preliminary training concept can be outlined, based on the operator interviews.
- Application of the pre-validation. The pre-validation approach has been applied to several validation tasks in Finnish NPPs, such as a case study of a Large Screen Display (LSD) pilot of Fortum Loviisa NPP employing an E&D simulator, with the aim to gather both preliminary information of the usability of the prototype and experiences from the operators.

Main results and conclusions

- The CASU methodology has been developed and tested by VTT while accomplishing real evaluation task in the context of design of control room upgrades or in drafting solutions for future control rooms in Finnish NPPs.
 - Validation tasks in the modernization projects of TVO Olkiluoto NPP and, especially, Fortum Loviisa NPP. Until now has accomplished a two step validation for the changes in the control room in the first phase of the four-phased Instrumentation and Control (I&C) and control room modernization process.
 - Design-oriented projects for developing new concepts, like information rich displays or ecological interface designs. The usability case approach has been employed for the FITNESS control station concept operational, in a simulator test involving Finnish and French NPP operators.
- Lessons learned of the application of the pre-validation approach to several validation tasks in Finnish NPPs were:

- Pre-validation tests serve for further development of the designed system, as provide information of whether the design work is proceeding according to agreed plans. The designed system must be complete and detailed enough for the testing to be feasible. A large part of the target system has to be simulated. The smooth functioning of the simulator model is important.
- In the pre-validation phase, systems are tested in a modular fashion, individual tests focus on a specific set of control room HSIs, i.e., not tested as a part of the whole control room. Therefore, the inferences from pre-validation tests about the new concept of operations must be cautious.
- The question of reference is a key issue in the evaluation of technical systems. (1) In the evaluation of individual features of HSIs, the evaluation is based on the usability experts' judgment, and also standards and guidelines can be used. (2) In the evaluation of concept of operations, the expertise of simulator trainers and experienced operators are needed, which may be difficult to obtain.
- Usability experts' independence from the design team is important and the independence increases as the design process progresses. It is preferable that the usability experts are responsible for all the main activities of testing, including the selection and modeling of tasks and scenarios. In the application cases, the representatives of the design team were mainly responsible for the planning phase.
- The most important phases in pre-validation are modeling and assessment:
 - a. Detailed enough models of the tasks allow attending to key activities during simulation runs and asking relevant questions during process tracing interviews.
 - b. Assess the safety implications of the design, or its impact on the concept of operations, constitutes a real challenge. The aim is to evaluate how well the new system fulfils the functional criteria of systems usability: instrumental –investigate to what degree the new systems support operational demands–, psychological – evaluate how well the operators' coordination with the tools and procedures, and orienting to the core task demands, have succeeded–, and communicative –judge whether the overall significance of singular events were comprehended and shared within the crew–.
- A representative set of test scenarios, covering all the tasks of the new HSIs, should be selected.
- A sufficient number of complete crews of operators with different levels of expertise are desirable to be recruited, with the operators being a representative sample of the NPP operating crews.
- Validation of NPP control systems is typically considered as an integrated activity at the final stage of the design and HFE process (NUREG-0711). A new approach to V&V is proposed, in which the evaluation is a longitudinal and distributed activity in an integrated design process. The series of pre-validation tests conducted can thus support the more integrated validation of the CR HSIs by providing cumulative evidence of their systems usability.

Recommendations

- Ensure sufficient independency in the ISV. In CASU method, the reference used in the validation is not defined within the design. Good performance in process control is explicated in modeling activity in which the core task of operations is considered. Also the scenarios used in the validation are modeled.
- As research needs, at least two issues needed further elaboration: the metrics used to analyze performance and interface features, and the reference used in evaluations.
- The methods used are theoretically well founded and the results get well documented.

Further research

- On-going project. The approach for ISV is being tested in Finnish NPPs.
- Pointed out as future development needs of the CASU method:
 - The adaptability of the evaluation framework to different design situations is an important requirement, which is being considered in articulating the usability case reference approach.
 - The reliability of the qualitative assessments accomplished by the evaluators in various phases of the analysis. Since the approach assumes that the evaluation metrics is tuned to the specific evaluation situation, it needs to have a handy tool kit to test the operationalization of the evaluation criteria. The approach is meant to be an expert tool used by a multidisciplinary evaluation team. The team may develop into an independent but contextually well-informed HFE reviewer of a design process.
- Some open questions are on the use of pre-validation test data for the final validation of a system and how a set of pre-validation tests can support the validation by providing cumulative evidence of the functionality and usability of the system.

References

- Laarni, J., Savioja, P., Karvonen, H., Norros, L. (2011). Pre-validation of nuclear power plant control room design. In: D. Harris (ed.), *Engineering Psychology and Cognitive Ergonomics*, HCI 2011, pp. 404-413. Berlin: Springer-Verlag Berlin and Heidelberg GmbH & Co. K.
 - Norros, L. (2004). *Acting under uncertainty. The core-task analysis in ecological study of work*. VTT publications 546. Espoo, Finland: VTT Technical Research Centre of Finland. 241 pp. <http://www.vtt.fi/inf/pdf/publications/2004/P546.pdf>
 - Norros, L., Savioja, P. (2005). Theoretical justification of performance indicators for integrated validation of complex systems. In *Proceedings of the Man-Technology-Organisation of the Enlarged Halden Programme Group Meeting (EHPG)*, October 17-21, 2005, Lillehammer, Norway.
 - Norros, L., Savioja, P. (2007). Towards a theory and method for usability evaluation of complex human-technology systems. *Activités*, 4(2), 143-150.
 - Norros, L., Savioja, P., Salo, L. (2009). Approach to integrated system validation of NPP control rooms. In *Proceedings of the Sixth American Nuclear Society International Topical Meeting on Nuclear Plant, Instrumentation, Control and Human-Machine Interface Technologies (NPICT&HMIT)*, April 5-9, 2009, Knoxville, Tennessee, USA, pp. 1998-2010.
 - Savioja, P., Norros, L. (2008). Systems usability – promoting core-task oriented work practices. In: E. Law, E. T. Hvannberg, G. Cocton (eds.), *Maturing usability: quality in software, interaction and value*, pp. 123-143. London: Springer.
 - Savioja, P., Norros, L., Salo, L., Laarni, J., Liinasuo, M. (2010). Integrated system validation: the questions of independence and reference. In *Proceedings of the Man-Technology-Organisation of the Enlarged Halden Programme Group Meeting (EHPG)*, March 14-19, 2010, Storefjell, Norway.
- Additional references:
- Laarni, J., Koskinen, H., Salo, L., Norros, L., Braseth, N., Nurmilaukas, V. (2009). Evaluation of the Fortum IRD pilot. In *Proceedings of the Sixth American Nuclear Society International Topical Meeting on Nuclear Plant, Instrumentation, Control and Human-Machine Interface Technologies (NPICT&HMIT)*, April 5-9, 2009, Knoxville, Tennessee, USA.
 - Laarni, J., Norros, L., Rinttilä, E. (2007). Control room modernization from an evolutionary

point of view – Experiences gained at Loviisa NPP. In *Proceedings of the Workshop on Future Control Station Designs and Human Performance Issues in Nuclear Power Plants* NEA/CSNI/R(2007)8, Paris, France: Organisation for Economic Co-operation and Development (OECD), pp. 409-429.

- Norros, L. and Savioja, P. (2005). Validation of NPP control rooms: new HF assessment methods. *Eurosafe Tribune*, 12-14.
- Norros, L. and Savioja, P. (2004). Modeling the activity system – development of an evaluation method for integrated system validation. In *Proceedings of the Man-Technology-Organisation of the Enlarged Halden Programme Group Meeting (EHPG)*, May 9-14, 2004, Sandefjord, Norway.
- Norros, L., Koskinen, H., Hildebrandt, M., Paulus, V., Gauthier, B., Origin, A. (2011). Methodology for evaluation of innovative concepts: case FITNESS control station concept. In *Proceedings of the Man-Technology-Organisation of the Enlarged Halden Programme Group Meeting (EHPG)*, October 2-7, 2011, Sandefjord, Norway.
- Norros, L., Liinasuo, M., Hutton, R. (2011). Evaluating the potential of new technological tools for safety critical work. *Interacting with computers*, 23, 299-307.
- Norros, L., Nuutinen, M. (2005). Performance-based usability evaluation of a safety information and alarm system. *International Journal of Human-Computer Studies*, 63, 328–361.
- Norros, L., Savioja, P. (2004). *Usability evaluation of complex systems. A literature review*. STUK-YTO-TR 204. Helsinki, Finland: STUK. 44 pp.
- Nuutinen, M., Norros, L. (2009). Core task analysis in accident investigation: analysis of maritime accidents in piloting situations. *Cognition, Technology and Work*, 11, 129-150.
- Savioja, P. and Norros, L. (2004). Evaluation of operator practices as a means of integrated system validation. In *Proceedings of the Fourth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human Machine Interface Technology (NPICT&HMIT)*, September 19-22, 2004, Columbus, Ohio, USA.
- Savioja, P. Norros, L. Salo, L. Kivikunnas, S. and Karppinen, J. (2005). Core-task analysis in requirements gathering for an adaptive batch process control interface. In *Proceedings of the Annual Conference of the European Association of Cognitive Ergonomics*, September 29- October 1, 2005, Crete, Greece, pp. 19-25.

7.2.CASE STUDY 2: HUMAN FACTORS EVALUATION OF CONTROL ROOM OF EPR FLAMANVILLE UNIT 3 – FRANCE

| |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Study reference |
| EDF. Human factors evaluation program of the European Pressurized Reactor (EPR) control room of Flamanville Unit 3 NPP. |
| Domain of origin |
| Nuclear power plant. |
| Type of study |
| Simulation of future operating situations: user tests based on scenarios, with a qualitative approach. The participants are end users –their status has changed as the project has progressed. During the design process of the EPR control room, several test campaigns are being carried out, with the data collection starting in 2002 and on going. |

Purpose of the study

The human factors evaluation program of the EPR project for the operating means and the control room design has been constructed over the last ten years in EDF R&D. The validation evaluation is carried out in subsequent phases, during the design of an EPR NPP that is under construction at the Flamanville site in France. The human factors validation is associated with the decision to declare definitive start-up of the system.

One of the test campaign (the first evaluation with a mock-up of the operating means) focused on the computerized operating principles, covering from 2002 to 2003, is detailed presented in a special section of methods and measures of the first evaluation campaign of this summary table.

Theoretical underpinning

- Sociotechnical system of operation (man-machine-interfaces connections/procedures/teams/organization). Applied ergonomics. User-centered design. The HFE is a pro-active approach, for anticipating the risks and difficulties related to future operating situations, from the phases immediately upstream of the design.
- Standards for user-centered design and ergonomics, such as ISO 9241 (1998), ISO 11064 (2004), and IEC 60964 (2009) are referenced. For design and engineering of human factors refers to literature in nuclear area, such as NUREG-0700 (2002), NUREG-0711, NUREG/CR-6393 and EPRI (2005).

Issues of integrated system validation

Human factors evaluation campaigns. Methods. Simulations. Scenarios. Participants. Evaluation team. A case study.

Validation stages

- Definition of ISV. The human factors validation is considered a special case of the evaluation, and comes at the end of the design phase with trained teams, after initial feedback at the start of operation. For the previous stages, EDF refers to evaluation processes that measure the efficiency of a system or subsystem and suggests improvements. The definition of validation is: “human factors validation is associated with the decision to declare definitive start-up of a system. This decision is based on the evaluations carried out throughout the design process and on the first operational feedback”.
- Overall evaluation process. The evaluation of the EPR is a continuous process structured around two types of evaluation campaigns of the future control room and targeted evaluation.
 - 1) Evaluation campaign of the future control room (such as procedures, imagery and, organization).
 - The first campaign was performed in 2002-2003, on a static mock-up of the operating means planned for the EPR, and then with a dynamic mockup –computer mock-up showing the operation concepts– coupled to the process simulator of a Pressurized Water Reactor (PWR). The aim was to validate and consolidate the operating principles, particularly the layout of the computerized operating stations, the structuring of the information in imaging or in operating documents, and the usefulness and feasibility of certain Man-Machine Interfaces (MMI) functionalities.
 - A second campaign began in 2009, and it involved several phases from 2009 to 2011. The aim was to evaluate the final design for all operating means with an EPR operation simulator and the future crews.
 - 2) Targeted evaluation, consisted of five campaigns:
 - In 2005, the aim was to validate the principles and designs of incidental/accidental operation, in a dynamic mock-up, focusing in the organization’s evolution, the

procedures structure, the team, the automatic diagnosis, and their interactions.

- In 2006, the simulation used a full scale control room static mock-up in a wooden model to evaluate the physical layout of the work stations and the layout of the future control room.
- In 2007, the principles for writing operating documents were evaluated.
- In 2008, the simulation took place on a full scale conventional safety panel static mock-up in a wooden model to evaluate the specifications for the layout of the controls and information from the conventional operating means. Served as a backup in the event of loss of the computerized operating means.
- In 2008, tests were carried out for incidental/accidental operation, in a dynamic mock-up, to increase perception of the new organization of the operations teams (analysis of the new teamwork organization) and, as a result, the means required for this organization.

Methods and measures

The EPR is a new generation of nuclear reactor, the first Generation III+ plant, which uses digital I&C. The Flamanville Unit 3 EPR is under construction in France.

- **Methods: simulations.** Simulation consists of producing as faithfully as possible a situation. The simulation aims to create a future work context, by using future operating means (interfaces, procedures, and operating imaging), by recreating scenarios based on knowledge of operating situations that are real, normal, and incidental/accidental and by associating end users with the expected target organization.

Simulating complex work situations allows observation of teams' performance in interaction with the design choices and the technical solutions. Simulation is a tool that is aimed at reproducing known situations or attempting to produce future situations as a whole. Simulation is used to play a set of previously defined and identified variables (Pavard, 2002⁶), to explore a change of situation in interaction with the new operating means being designed, and to evaluate their impact on performance and safety.

The simulations have been adapted to the requirements of the design stages of the project. Three simulation levels were used for the evaluations throughout the design process (prior to commissioning): static mock-up (on paper for screenshots or instructions, on the computer screen for MMI specifications or images on a wooden scale model for fitting out the control room), dynamic mock-up coupled with a PWR simulator (for carrying out overall or targeted evaluations of operating means), and full scale EPR simulator.

- Simulation based on static models corresponds to the first phases of design, when design principles are defined based on descriptions and representations of the design (on paper, in electronic format, or in a scale model). The simulations on static mock-up were relatively simple and targeted; however, they allowed a better perception of user requirements. They were relatively "light" simulations to set up and allowed rapid iteration of a design phase. Each simulation took from 1 to 6 months of preparation.

The training of the participant' operators in these tests (who were working on other reactors) was a half-day maximum, and consisted of presentation of the evaluation objectives and the procedure, the main guidelines taken to design the EPR operating means to situate the operational context with respect to their current practices, and the phase of taking on board the objects to be evaluated.

Data collection also depended on the objectives, but the time needed varied from a day (two or three teams in the same day) to twenty days (e.g., four teams during a week).

⁶ Pavard, B. (2002). Complexity paradigm as a framework for the study of cooperative systems. In P. Salembier and T. H. Benckroun (Eds.), *Cooperation and complexity. Revue d'Intelligence Artificielle*, 16(4-5), 419-442.

Data analysis can be very time-consuming, from 1 to 4 months, depending on the industrial constraints.

- Simulation with dynamic models makes possible a more representative and complex level of interaction among the end user, the proposed means, and the dynamic performance of the installation, which favors a more thorough analysis of the likely future activity that is starting to be deployed.

Depending on the campaigns and the area covered by the evaluations, participation of active operators on other reactors required a short training course of half day or one day, to handle and become familiar with the dynamic performance of the mock-up and the procedure (during mini simulations).

Three test sessions were conducted by simulation with dynamic mock-up (computer mock-up showing the operation's concepts) coupled with the PWR simulator.

- Simulations with a full-scale simulator were organized, from 2009 to 2011, according to the phases of representativeness of the full-scale EPR simulator. The aim was to evaluate the final design for all operating means with an EPR simulator to make the decision to move on to the on-site commissioning phase (for first use in production). For ensuring that the interactions and connections between human-machine-organization-procedures work correctly, from both performance and efficiency of the teams, and reliability and safety.

Several end users (individually or teams) participated to try to compensate for individual variability (as experience of operation or site culture).

The complexity of the situations increased with the types of simulation. In static situations, a global control of variables exists and the interaction with users is limited, while with the full-scale simulator, the situations become more complex and the variables in place were not all controllable. The organization, the means, and the analysis also become more complex.

The campaign should be planned 1 or 2 years ahead. It takes approximately 2 or 3 months to perform, and 4 or 5 months are required for the data analysis.

- Participants: end users. The end users have to use the tool that has been designed, controlling the plant in the control room. The categories of end users have varied according to the progress of the project, users' experience, and their methods of participation. In the first campaigns, the end users were operations employees, more or less experienced, who were not necessarily going to operate the EPR, as the recruitment began seven years later, but considered to be representative of future users. For the latest evaluation campaigns, real future end users (operators and operations shift managers of EPR operations) started to be recruited for the Flamanville site: experienced in operating reactors or without operating experience (having to undergo an additional training course).

The end users contributed in several ways:

- Advise by using their expertise concerning operation.
- Test subjects in the evaluations, by contributing in: analysis and characterization of future activity, evaluation and validation of design choices, identification of precise and organizational technical difficulties, proposal of new solutions for the design, and also participating in the construction and validation of realistic and representative scenarios.
- Contribute to specific multidisciplinary work groups.
- Participate in the detailed design in the design teams.
- Training. Depending on the test campaigns, prior training requirements were expressed differently, and specific training programs were developed prior to the evaluations. During the human factors test campaigns, users follow a mini training course about the new process and the new design choice. When getting nearer to the full-scale simulator, the training required becomes longer –a week minimum for a team having operation experience.

Using the same teams during successive campaigns reduced the training required for the new campaign.

- Scenarios. The simulations are based on the construction of realistic and representative scenarios of the future likely operating activity.

1) The scenario is a complex entity to be built during each phase of the human factors tests. A scenario is defined as “series of actions or sequences of actions by an individual or a group of individuals in a work situation taking place in conditions and in a hypothetical organisational context” (Maline, 1994, pp. 70⁷). The scenarios aim to provide a realistic picture of future activity while respecting its determining factors (such as characteristics of the personnel who will carry out the tasks, chronological sequences of tasks, environmental conditions, equipment and work tools and production targets).

For developing the scenarios, four dimensions are considered:

- Analysis of the project characteristics that will structure and modify the future work of the operators.
- Analysis of the activity in a reference situation –real work situation– for identifying key invariant elements in the operations activity, i.e., will be in the future work situations. The operation of the EPR will be highly automated and computerized. Therefore, the activity of the operators will change in terms of knowledge, cognitive requirements, and skills. Scenarios will aim to anticipate operator’s behavior in interaction with the work tools: the difficulties, the risks, and the requirements, especially skills and training.
- Linking of the characteristics of the project and the reference situations give the characteristic action situations (simulations). These situations lead to a set of determining factors, the simultaneous presence of which will structure the activity. Their purpose is to contribute to the formulation of markers for the design and construction of simulation scenarios.
- Construction of the scenario will lead to a series of simulations –characteristic action situations– by integrating a temporal dimension and a certain number of criteria associated with the work organization and the human factors evaluation objectives.

A scenario cannot really be reused from one test campaign to another; however, the principles and objectives may remain more or less the same.

2) A scenario is constructed according to the aims to be achieved, the principles, the objectives and the constraints that are qualitative, quantitative, and technical. The objectives of human factors evaluations usually overlap and vary according to the progress of the design project, such as validate design choices on operations interfaces, operations procedures, and/or the organization, evaluate the team’s capacity to handle specific accidental situations, validate the physical layout of workstations or analyze the team’s workload in specific situations.

The objectives will mainly be determined, but not only, by the human factors experts. The construction of scenarios involves different skills from human factors experts, designers, training instructors, other technicians, operators and operations managers.

The progress of the project –the available procedures, the status of the mock-ups and/or simulator– will determine the scenarios to be constructed. Simulations have to remain ecological and relevant for the project, and the situations not played out will be carried forward to the next evaluation, so that at the end of the evaluation process the area covered is representative of the variability of operation situations of the life cycle of the installation.

3) Representativeness of scenarios: multidisciplinary expertise. The sample of scenarios

⁷ Maline, J. (1994). *Simuler le travail, une aide à la conduite de projet*. Lyon: ANACT.

will be representative of only a part of the reality that is shared by numerous experts, to ensure that certain types of situations are represented. The scenarios integrated normal operations and accidental/incidental operation situations.

In the test campaigns, each scenario was tested to ensure linking between the different sequences and the adaptation of implemented resources. The number of scenarios varied in relation to the objectives of the evaluation, the available time and operating means for the tests. Several scenarios were necessary, each being made up of different simulations. For overall evaluations, between 10 to 15 scenarios were used, each of them lasting from 3 to 4 hours of simulation. The same simulations were tested with different potential end users to guarantee the representativeness of the results. The number of end users depended on the requirements of the evaluations, the users profile, the number and diversity of the planned scenarios, and the project constraints. Experienced operators (between 2 to 15 years of experience) worked in full teams, and a minimum of three complete teams (i.e., nine users) participated in an evaluation session.

Methods and measures of the first evaluation campaign

A case study of the first evaluation campaign is described in a separated section on methods and measures to present an overview of both the overall evaluation process and the specific evaluation campaign. The initial evaluation was based on the implementation of a test campaign on a mock-up connected to a process simulator, with the participation of operations teams, and took place between 2002 and 2003.

The main objective of the first campaign was to evaluate the feasibility of the operating principles to test new computerized operating concepts that differ from the N4 NPP series. The evaluation was carried out early in the project, i.e., prior to the definitive specifications for the supplier of I&C system, to the phases of detailed specifications of the MMI and to the design of the operating procedures. Another objective was to involve the operations teams in the design process by ensuring that the operator identified all requirements for the teams to carry out the operating activities effectively, efficiently, and safe, as well as by collecting the operator proposals about the detailed design of operating means (such as layout of work stations, MMI, and instructions).

- Tests preparation. The preparation of overall evaluation campaigns was relatively long. The decision to carry out the test campaign was made in June 2001, two work groups operated from September 2001 to June 2002, the sites were approached at the end of 2001 to make teams available, the first phase of tests on the mock-up were from October 2002 to January 2003, and the second phase of tests was from April to June 2003.
 - A multidisciplinary team –composed of specialists on human factors, I&C and process, and former operators– prepared the tests and analyzed the results.

A first working group defined the contents and volume of the tests, the evaluation themes, the scenarios, and the logical aspects. Then human factors specialists defined the data collection and the detailed protocol for controlling the tests and making initial human factors analysis. The multidisciplinary working group drafted the final summary of the tests.

A second working group produced a detailed specification of the MMI for operating the mock-up, listing the principles and requirements stated by the operator for the computerized operation of the EPR.
 - The tests took place in two phases, first on a static mock-up not connected to a process simulator, and then dynamic tests on a mock-up connected to a process simulator.
 - a. The test phase 1 dedicated three days to the training of each team on the mock-up's MMI and on the operation differences between their reactor and the process simulated on the test platform. Then the first two scenarios of normal

operation were run “by hand” during two days. The evaluations carried out concerned the layout of the workstations and the number of screens, the structuring and the contents of the images, the principles of navigation and the use of the dialogue mechanisms, the additional requirements concerning shift changes and finding out the status of the installation, and the role and contents of the synoptic system.

- b. The test phase 2 employed a mock-up connected to a process simulator, and lasted for two weeks. Each team played out eight scenarios of normal, downgraded, and accidental operation. In addition to the phase 1 themes, the evaluations looked at the production of normal operation transients, the activities of monitoring and supervision of the installation, the use of the synoptic system, the management of parallel activities, interruptions, and restarts of activity, alarm management, accidental operation and the use of automatic diagnosis, additional requirements on level 3 tools (outside process real-time operation), management of modifications to the operating procedures, supports for annotations of procedures, etc.
- The mock-up of the operating MMI was connected to a 900 MWe process simulator, and comprised two operating stations with four screens for operators and one workstation for the technical manager. The synoptic images were projected by two video projectors and a color printer made copies of screenshots.
The operating procedures and the periodic test ranges were adapted from the 900 MWe plant series. Almost 380 operating images were produced and 12 operating procedures were adapted.
 - Participants. Five operating teams –composed of two operators and a technical manager – participated voluntarily in the test campaign. Half of the sample had at least 10 years of experience in operating reactors. The sampling criteria concerned the type of I&C used: two teams from the N4 plant series (latest technology PWR installed in France with fully computerized I&C); two teams from the 1300 MWe plant series (second-generation PWR in France with traditional I&C), and one team from the 900 MWe plant series (first-generation PWR in France with traditional I&C).
 - Scenario preparation and elaboration. Analyses of the operating activities in both a traditional control room (900 MWe and 1300 MWe plant series) and a computerized control room (N4 plant series) were done for the preparation of the tests –structuring the evaluations in the context of the tests, identifying the simulations characteristic and the scenarios, and sizing the volume of the tests.
Ten scenarios were planned (two for phase 1 and eight for phase 2), consisting of thirty-five simulations of normal, incidental, or accidental operation. These scenarios were validated and run on the mock-up before the tests were carried out.
 - Evaluation team in the data collection. Two human factors observers, one or two technical observers, and a training instructor participated in the tests:
 - a. The human factors observers and the technical observers monitored the tests. The human factors specialists controlled the tests, made observations, and lead the interviews. The technical observers provided support for the human factors observers to evaluate the technical performance of the operation (key actions within the required time limits) carried out by the team and also answered the technical questions of the teams in relation to the progress of the scenarios.
 - b. The training instructor was responsible for training the teams in the simulated process (900 MWe). In the scenarios, controlled the simulator and played the role of personnel outside the control room. With the technical observers, the instructor also contributed to the evaluation of the technical performance of the

operation that was carried out by the team.

- Data collection. The data collection was mainly qualitative, and was based on the data resulting from three techniques: observation, interviews and questionnaires.
 - Observations were made and notes taken during the tests, according to a collection table (such as difficulties encountered, spoken expressions, communications between team members and workstation configuration). The aim was to have objective data that were essentially repeated during the different observations.
 - Group interviews were held after each test, to compare the points of view of all team members, encourage explanation of certain difficulties identified, and thus validate some of the observations. During the interviews, the imaging and the simulator could be used to share information and to discuss a particular point linked to operation.
 - Individual questionnaires on operator opinions were completed at the end of each test phase, with special themes such as the structuring of the operations imaging, the number of screens, or the alarm processing, and employed closed questions –with a rating scale and a free field for justifications– to place statements in order of importance. The questionnaires provided mainly subjective elements, and they completed and validated the results of observations on specific points.

Video and audio collection methods were not used. Although initially planned, they were abandoned during phase 1 because they did not provide real added value in the tests context and the level of analysis carried out, and were time-consuming and unsuited to the industrial constraints of the project.

The data collection report prepared for each test phase was then validated by each of the operations teams. In total, the data collection carried out during the tests involved more than 80 hours of observations, 150 hours of interviews, and 30 opinion questionnaires summarized in 10 test reports.

- Data analysis. Two stages of analysis were performed, an initial level of human factors analysis and a second level of analysis by a multidisciplinary work group (specialists on human factors, I&C, process, designers and former operators).

The human factors analysis was based mainly on qualitative criteria to evaluate the impact of the operating principles on the operating activities (e.g., the operator's ability to detect an alarm, to detect a sensor default, to solve a problem, to handle the interruptions, and to resume activities), and the usefulness of the operating means (i.e., the functional response they provide to requirements of operating activities and the aspects related to their usability; and how easily they could be implemented and taken on board by the participating operations teams). The summary offered an analysis of the different design options evaluated, highlighting the positive points, the points that could be improved, and the points that should be subjects of further studies.

On the basis of the initial human factors analysis and the constraints –technical feasibility of requests, production cost and schedule–, the multidisciplinary working group decided whether the operating principles planned by the operator were acceptable. Also a program of additional studies was proposed. The summary of the tests and the study program were validated at a technical review attended by EDF managers and engineers.

Main results and conclusions

- The results of tests of the first evaluation campaign contributed to the design process in:
 - Allowing to made decisions for detailed design about the concepts of computerized operation and the validation of most of them. For instance, hybrid procedures (both on paper and computerized) were adopted to facilitate updating and to simplify understanding of the strategy for operators. Only the instructions for starting and stopping equipment and functions were computerized, while paper versions were used

the rest of the time.

- Validating the use of the automatic diagnosis in emergency operation, even if the usability of imagery had to be reviewed.
- Consolidating and completing the operator’s requirements. Specific needs in supervision or monitoring tools were identified for normal operations to help the operator anticipate and control events. One screen was added to the workstation, allowing the performance of two simultaneous activities and their monitoring in a dedicated screen. A sixth screen was integrated to access the office software.
- Contributing to technical exchanges with suppliers of digital I&C and to the specifications update (supervision tools, the fifth screen, the computerized procedures).
- Collecting numerous team proposals to feed the detailed specifications phases (e.g., the supervising imagery for control room monitoring, the synoptic imagery according to the state of the reactor).
- Prioritizing remain design problems and constructing the program of additional studies that were implemented in the next stage of the project.
- Using the tests as a good educational support for the engineers involved in the design and the project decision makers, by better understanding what future operating situations would be and the interactions between end users and design objects.
- The conclusions from the evaluation campaigns indicated that:
 - The test campaigns have proven to be an efficient method for ensuring suitability among the operating means (procedures, interfaces, imaging, organization, etc.), operating requirements (as supervision of the plant series, management, accidental incidental operation), and the characteristics of the teams (training and experience).
 - The feedback from the evaluation campaigns was positive, despite being a “heavy-duty” procedure. The investments in terms of time, human resources, costs, and logistics may seem large, yet the results have systematically enriched the project and allowed to respond to certain requirements of the Safety Authority. The authors are involved with operationalizing effectively and at less cost the human factors analysis of operational situations with respect to designers and the operator as well as future users.

Recommendations

- The test campaigns for the continuous evaluation procedure were carried out by a multidisciplinary team from the starting of the project. Some tasks were specific to human experts, such as analysis of the existing work situation and identification of characteristic work situations that may be carried out in the context of scenarios, but other tasks, as the preparation of instructions, the specific imaging and the technical validation of scenarios, should be carried out by other experts. The test campaigns involved real teamwork.
- The evaluation programs, such as the number and types of evaluation sessions that will be necessary and at what points, are to be built into the running of the project. The human factors expert had to state the appropriate times for evaluation in collaboration with the various parties involved in the project and ensure that a specific working group is set up during each test campaign. The preparation work is a group effort, and the human factors expert has an important role in monitoring and setting up mock-ups and prototypes, monitoring the progress of the status of the full-scale simulator (what can be simulated and with what resources), and also has to guarantee the availability of a representative sample of end users (a difficult task).
- The scenario preparation involves laborious teamwork during several months to be representative and relevant. The analysis phase mainly involved the human factors experts, but the results have to be validated and discussed with the users who participated in the evaluations and with other experts. Feedback to the design team is a vital point of the

| |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p>procedure. The results need to be reworked to obtain specific recommendations concerning the development of operating means. The aspects to be looked at in more depth are extracted, which could be subjects of either another study or a specific working group. At best, certain points will be validated. Therefore, the evaluation procedure should be continuous and iterative in a complex design project.</p> |
| <p>Further research</p> <ul style="list-style-type: none"> • On-going project. The test campaigns of the EPR are being carried out since 2002. • The evaluation program defines that the next human factors tests will be carried out with a whole team: action operator, strategy operator, chief operator and safety engineer. Three teams will participate in the evaluation program of the simulator phases 2 and 3, and another three teams will participate in the simulator phase 4. <p>The simulator phase 2 will consist of 30 days of simulation: 10 sessions during 10 days by each team (3-4 hours of simulation plus 3-4 hours of debriefing). The scenarios will be based on the knowledge of the probable future situation in both normal and emergency operation (incidental and accidental situations). The scenarios will be constructed by different experts –future end users involved in the design project, engineers, human factors experts, training staff, operation staff– and the sequences and the operation activity will be technically validated before the simulations. Seventy situations in emergency (twenty-seven accidental situation and twelve incidental situations) and normal operation (thirty-one normal situations) will be presented in a total of fourteen scenarios. Each of the assessed topics has several hypotheses associated. For example, the work organization consisted of ninety-two hypothesis taking into account the individual and the collective point of view, the operating procedures had twenty-four hypotheses or the MMI considered fifty-five hypotheses.</p> |
| <p>References</p> <ul style="list-style-type: none"> – De la Garza, C. and Labarthe J.-P. (2010). Contribution to the human factors evaluation program of the EPR operating means. Some elements for discussion. In Braarud, P. Ø., Nystad, E., Strand, S., Skråning, G., Bye, A., Hildebrandt, M., and Massaiu, S. (2010). <i>The Halden Reactor Project Meeting on Integrated System Validation (ISV) – Status of Current Approaches to ISV and R&D Needs</i> (HWR-939). Halden, Norway: OECD Halden Reactor Project. – Labarthe J.-P., De la Garza, C. (2011). The human factors evaluation program of a control room: the French EPR approach. <i>Human Factors and Ergonomics in Manufacturing & Service Industries</i>, 21(4), 331-349. <p>Additional references:</p> <ul style="list-style-type: none"> – De la Garza, C., Labarthe, J.-P. and Graglia, L. (2012). The contribution of ergonomics to risk analysis in the design process: the case of a future control room. <i>Work</i>, 41, 730-736. |

7.3.CASE STUDY 3: HUMAN FACTORS VALIDATION SYSTEM AND PERFORMANCE MEASURES OF CONTROL ROOM OF APR1400 – SOUTH KOREA

| |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p>Study reference</p> <p>Korea Advanced Institute of Science and Technology (KAIST) and Korea Electric Power Research Institute (KEPRI). Human factors validation system and performance measures for the Advanced Power Reactor 1400MWe (APR1400) in South Korea.</p> |
| <p>Domain of origin</p> |

| |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Nuclear power plant. |
| Type of study |
| Simulation. The HSI design in the advanced main control room of Advanced Power Reactor 1400MWe (APR1400) can be validated through performance-based tests to determine whether it acceptably supports safe operation of the plant. |
| Purpose of the study |
| Development of performance measures for ISV as well as the development of a human factors validation system for the advanced control room of the APR1400. The digital MCR design needs a comprehensive V&V process to get the license for construction. <ul style="list-style-type: none"> – Human performance measures were developed in order to validate the HSI design in the advanced MCR of APR1400, taking into account considerations and constraints –such as the environment, the needs for a practical and economic evaluation, or the suitability of evaluation criteria–. The measures for the human performance evaluation were related to plant performance, personnel task performance, situation awareness, workload, teamwork, and anthropometric/physiological factors. – A human factors validation system was developed, providing high degrees of physical, functional, and dynamic fidelities. The human factors validation system for the advanced control room of the APR1400 is composed of process/plant models, HSIs (which include all facilities in the APR1400 MCR, such as Large Display Panels (LDPs), three identified operator workstations, and a safety consol), and the Human Performance Evaluation Support System (HUPESS). The HUPESS is expected to support the ISV of the advanced MCR for the license of Shin-Kori Unit 3&4 NPPs (APR1400 type), which are under construction in South-Korea. |
| Theoretical underpinning |
| <ul style="list-style-type: none"> • As described in NUREG-1624⁸, the operator’s tasks are generally performed through a series of cognitive activities such as monitoring the environment, detecting data or information, understanding and assessing the situation, diagnosing the symptoms, decision-making, planning responses, and implementing the responses. The MMI design of a MCR should have capability to support the operators in performing the cognitive activities by providing sufficient and timely data and information in an appropriate format. Effective means for the system control should be provided in an integrated manner as well. • The development of the measures was based on theoretical and empirical background, and also on the regulatory guidelines for ISV, such as NUREG-0711 and NUREG/CR-6393. |
| Issues of integrated system validation |
| Development of measures. Performance criteria: requirement, benchmark and expert judgment referenced approach. Development of human factors validation system. |
| Validation stages |
| <ul style="list-style-type: none"> • Validation concept. The HFE program is implemented based on the HFE PRM of NUREG-0711. The objective of the ISV is to provide evidence that the integrated system adequately supports plant personnel in the safe operation of the NPP (NUREG/CR-6393). ISV can provide evidence that the integrated design remains within acceptable performance |

⁸ Barriere, M., Bley, D., Cooper, S., Forester, J., Kolaczowski, A., Luckas, W., Parry, G., Ramey-Smith, A., Thompson, C., Whitehead, D. and Wreathall, J. (2000). *Technical Basis and Implementation Guidelines for a Technique for Human Event Analysis (ATHEANA)* (NUREG-1624), Rev. 1. Washington, D. C.: US NRC.

envelopes.

Methods and measures

The main control room of the APR1400 consists of Cathode Ray Tube (CRT) or Liquid Crystal Display (LCD) based displays, large display panels, soft-controls, a computerized procedure system, and an advanced alarm system. The plant involves passive safety features, digital I&C, and computerized MCR. The advanced control room design incorporates extensive automation of facilities to enhance operator's decision making and to reduce operator's workload. The APR1400 is applied to Shin-Kori Unit 3&4 and the digital based MCR design requires a V&V process.

- Measures.

- Considerations and constraints. The following considerations and constraints on the development of human performance measures were taken into account:
 - a. The operating environment in an advanced MCR is changed from the conventional analog based MMI to digitalized one, such as an increased automation, development of compact and computer-based workstations, and operator aids. Special attention should be paid to operator task performance and cognitive measures.
 - b. The evaluation of human performance should be practical to provide technical basis in order to get the operation license and economic. Techniques proven to be empirically practical in various industries were adopted as main measures with some modifications. In addition, complementary measures were developed for the evaluation of plant performance, personnel task performance, situation awareness, and workload.
 - c. The evaluation criteria for the performance measures should be clear, and if it is not applicable, the criteria should be reasonable in the state of the art. Empirically proven techniques used in nuclear industry were adopted as main measure for utilizing the results of the studies as reference criteria. Main measures were used to determine whether the performance was acceptable or not, whereas complementary measures were used to compare and scrutinize performance among operators or shifts or supplement the limitation of the main measures.
- Type of measures. Both product measures –assessment of results– and process measures –assessment of how the result was achieved– were developed. In the following, the human performance measures are described with the performance criteria.
- Plant performance. The operators' performance can be evaluated by observing whether the plant system is operated within acceptable safety level, which is specified by the NPP process parameters. Plant performance refers to operators' performance (crew performance) measured by observing, analyzing, and evaluating process parameters. Since the achievement of safety and/or operational goals in NPPs is generally determined by values of process parameters, the plant performance is directly interpreted into whether the goals in NPPs are achieved. There are usually values (e.g., set-points) required to assure the safety of NPPs (or the sub-systems) in each of process parameters. Attention should be paid to the preparation of test scenarios (i.e., being designed so that effects of MMI design can be manifested in operators' performance), the selection of important process parameters (i.e., being sensitive to and representative of operators' performance) and an integrated analysis of the plant performance with the other measures.
 - a. Main measure: operational limits. The evaluation criterion is based on the requirement referenced comparison. The process SMEs select important process parameters (empirically 5 to 7) for each test scenario. The upper and lower operational limits (within acceptable range) for

the safe operation of NPPs are determined by the process SMEs, after reviewing operating procedures, technical specifications, safety analysis reports, and design documents. During a validation test, if the values of the selected parameters (simulator logging data) don't exceed the upper and lower limits, the plant performance is evaluated as acceptable.

- b. Complementary measure: discrepancy score and elapsed time from event to target range. The evaluation criteria are based on both requirement and expert-judgment referenced comparisons.

During the validation test, the discrepancies between operationally suitable values and the observed values in the selected process parameters are calculated. SMEs (process experts) assessed the operationally suitable value as a range value, with upper and lower bounds, and represent good performance expected for a specific scenario. Also the assessment of the operationally suitable value should be based on operating procedures, technical specifications, safety analysis reports, and design documents. If the value of a process parameter is getting beyond or under the range, the discrepancy is used for calculation of the complementary measure. A low total discrepancy means better plant performance. The measure is used for comparing the performance among the crews or test scenarios rather than for determining the acceptability.

Also, at the end of test scenarios, the elapsed time from an event to getting into the target range (range of values) in each of the selected process parameters is calculated with simulator logging data. Shorter time spent in accomplishing a task goal represents good performance. Considering some fluctuation in the parameter, the measure is the time when the parameter is stabilized.

- Personnel task performance. Personnel task measures can reveal potential human performance problems, which were not found in the evaluation of the plant performance. Personnel tasks in the MCR are series of cognitive activities. Therefore, the operators' tasks can be evaluated by observing whether they monitor or detect the relevant data or information, perform correct responses, and the sequence of the series of activities.

- a. Main measure: confirming indispensable tasks and completion time. The evaluation criterion is based on both requirement and expert-judgment referenced comparisons. Personnel task performance can be evaluated by observing whether the operators monitor and detect the appropriate data and information, perform appropriate responses, and the sequence of the processes. A validation test scenario is hierarchically analyzed to develop the optimal scenario solution; the operating procedure provides the guide for the optimal solution. The main goal has to be accomplished in a scenario, and breaks down into the sub-goals to achieve it; the sub-goals can also break down. There are detections, operations, and sequences to achieve the relevant sub-goal in the next rank. Detections and operations break down into detailed tasks to achieve the relevant detections and operations. Tasks located in the bottom rank comprise a crew's tasks required for completion of the main goal. Top-down and bottom-up approaches are utilized for the development of the optimal solution. Indispensable tasks required for safe NPP operation are determined by process SMEs. During the test, SMEs (the same or other process experts) observe the operators' activities, collect data (such as operators' speech, behavior, cognitive process, and logging data), and then evaluate whether the tasks located in the bottom rank are appropriately performed or not. If all the indispensable tasks are satisfied, personnel task performance is considered acceptable. In the case that the operators implement the tasks in different way, the SMEs should check and record the operators' activities during the test and then some part of the optimal solution are

revised based on the observed activities after the test. The task performance is reevaluated with the revised solution and the collected data.

The task completion time is also evaluated. Time to complete each of the tasks located in the bottom rank is evaluated based on SMEs. The summation of the evaluated times can be interpreted as a required time to complete a goal. If the real time spent for the completion of a goal in a test is less than or equal to the required time, time performance of the personnel task is acceptable.

- b. Complementary measure: scoring task performance. The evaluation criterion is based on the expert-judgment referenced comparison.

Scoring the task performance can be used for analyzing and comparing performance among crews or test scenarios. The procedure was: 1) the weights of the elements in the optimal solution are calculated using analytic hierarchy process, 2) the operators' activities are observed and evaluated during a test, 3) process SMEs evaluate whether the respective tasks are satisfied in an appropriate sequence, and 4) the task performance is scored with the observed and evaluated data and the weights of the tasks. Higher score means higher task performance.

- Situation awareness (SA). The operator's actions must be based on identification of the operational state of the system. Situation awareness is frequently considered as a crucial key to improve performance and reduce error. As the operator's tasks in NPPs can be summarized as a series of cognitive activities, the tasks can be significantly influenced by the operators' SA.

- a. Main measure: KSAX. The evaluation criterion is based on the benchmark referenced comparison. The KSAX results from an antecedent study⁹ –evaluation of suitability for the design of soft control and safety console for the APR1400– is the criterion for the ISV.

KSAX is a subjective ratings technique adapted from SART. After completion of a test, the operators subjectively assess their own SA on a rating scale and provide the reason of the rating. KSAX consists of several questions regarding the three levels of SA defined by Endsley. The rating scale is not fixed but a seven point scale is recommended, because the antecedent study used it. In the questions, SA in an advanced NPP is compared with SA of the already licensed NPPs. The operators who have been working in the licensed NPPs are selected as participants for the validation tests. If the result of SA evaluation in an advanced NPP is evaluated as better than or equal to that in the licensed NPP, the result of the SA evaluation is considered as acceptable.

- b. Complementary measure: continuous measure based on eye fixation measurement. The evaluation criterion is based on the expert-judgment referenced comparisons.

KSAX is evaluated subjectively after a test, not being possible to continuously measure the operator's SA, therefore, is complemented by a continuous measure based on eye fixation data. An analysis of the manner in which the operator's eyes move and fixate gives an indication of the information input, even though cannot tell the operator's SA exactly. The eye fixation on areas of interest (AOI), the time spent on AOIs, and the sequence of the fixations are used for the SA evaluation:

- The eye fixations on AOIs that are important for solving the problems can be considered as an index of monitoring and detection, which can be interpreted into the perception of the elements (level 1 SA).
- Time spent on the AOIs by the operators can be understood as an index for the

⁹ Cho S. J., et al. (2003). The Evaluation of Suitability for the Design of Soft Control and Safety Console for APR1400. Daejeon, Korea, KHNP, TR. A02NS04.S2003.EN8.

comprehension of their meaning (level 2 SA).

- The selective attention is associated with expectancy for the near future. The projection of the status in the near future (level 3 SA) can be inferred from the sequence of the eye fixations.

SMEs (process and/or human factors experts) analyze the eye fixation data after the completion of a test, focusing on specific periods representing the task steps in the optimal solution of the personnel task performance –the eye fixation data analyses require much effort and time. For each of the periods, SMEs evaluate the SA on three grades, as excellent, appropriate, or not appropriate.

- Workload. The operators play the role of supervisor or decision-maker rather than manual controller in advanced MCRs. The evaluation of the cognitive workload has been considered as one of the most important factors for the ISV.
 - a. Main measure: NASA Task Load Index (NASA-TLX). The evaluation criterion is based on the benchmark referenced comparison. The NASA-TLX results from antecedent studies^{9,10} for the APR1400 can be utilized as reference criteria for the ISV.

The subjective rating technique NASA-TLX is considered as an indicator related to the participants' internal experience. NASA-TLX divides the workload experience into six components: mental demand, physical demand, temporal demand, performance, effort, and frustration. After completion of a test, the operators subjectively assess their own workload on a rating scale and provide the reason for the rating. The use of a seven point scale is recommended, because the antecedent studies used it. The workload in an advanced NPP is compared with the workload of the already licensed NPPs. The workload evaluation is considered as acceptable if result of the NASA-TLX in an advanced NPP is evaluated as lower than or equal to that in the licensed NPP.

- b. Complementary measure: continuous measures based on eye movement measurement. The complementary measures are based on the expert-judgment referenced comparison.

The NASA-TLX is evaluated subjectively after the completion of a test, not being possible to continuously measure the operator's workload, therefore, are complemented by continuous measures based on eye movement data. SMEs perform the evaluation of the measures of cognitive workload: blink rate, blink duration, number of fixation, and fixation dwell time.

- Blinking refers to a complete or partial closure of the eye. The increased blink rate is used as a clue indicating the point that requires high level of concentration or attention. The duration and the number of eye blinks should decrease when the cognitive demands of the task increase.
- The eye fixation parameters include the number of fixations and the duration of the fixation (dwell time) on areas of interest. If an operator experiences higher cognitive workload, the number of fixations and the fixation dwell time are increased. The dwell time is an index of the resources required for information extraction from a single source.
- The eye fixation pattern (or visual scanning) is used as a diagnostic index of the source of workload within a multi-element display environment –evaluates the resource allocation.

¹⁰ Byun, S. N. and Choi, S. N. (2002). An evaluation of the operator mental workload of advanced control facilities in Korea next generation reactor. *Journal of Korean Institute of Industrial Engineers*, 28(2), pp. 178–186.

An experimental study to investigate the cognitive workload in complex diagnostic tasks, during simulated NPP operations, showed that the eye movement measures correlate with NASA-TLX and modified Cooper-Harper scale (MCH) scores.

- Teamwork. The Behaviorally Anchored Rating Scale (BARS) evaluates the teamwork. The evaluation criterion is based on the expert-judgment referenced comparisons. The BARS results on an antecedent APR1400 study⁹ can be utilized as reference criteria. The BARS include task focus/decision-making, crew coordination, communication, openness, and team spirit. In each of the components, several example behaviors (positive or negative) and anchors (or critical behaviors) indicating good/bad team interactions are identified by SMEs (process expert and/or human factors expert) during a test. The example behaviors and the anchors identified are used as criteria for final (or overall) rating of teamwork by the SMEs after the test. A rating scale of a seven point is recommended, as it was used previously⁹.
- Anthropometric/physiological factors. The evaluation criterion is based on both the requirement referenced (HFE V&V checklist) and the expert-judgment referenced comparisons.
Anthropometric and physiological factors include concerns such as visibility and audibility of indication, accessibility of control devices and manipulation, and the design and arrangement of equipment. As anthropometric and physiological factors were evaluated earlier in the design process –with HFE V&V checklist–, the focus is on those factors that can only be addressed in simulation with high fidelity operating conditions, such as the ability of the operators to effectively use or manipulate various controls, displays, workstations, or consoles in an integrated manner. Items related to anthropometric and physiological factors in HFE V&V checklist are selected before the validation test and then reconfirmed during the validation test by SMEs. Also it should be checked whether there are anthropometric and physiological problems caused by unexpected design faults, which can be performed during the test or after the test with audio/video (AV) recording data.
- Performance criteria. The safety of a NPP is not directly observed and is inferred from available evidence obtained through a series of performance-based tests. The integrated system is considered to support plant personnel in the safe operation if it is operating within acceptable performance ranges. The acceptability of the performance in each of the measures is evaluated based on performance criteria, as summarized in NUREG/CR-6393. The evaluation criterion of the measures is based on requirement, benchmark and/or expert-judgment referenced approaches, as above described.
- Human Performance Evaluation Support System. HUPRESS was developed for evaluating the human performance in an integrated and effective way. The development of the human factors validation system (facility) considered the aspects of HSI completeness, HSI physical fidelity, HSI functional fidelity, data completeness fidelity, data content fidelity, and data dynamics fidelity. The validation facility should also meet the requirements of ANSI/ANS 3.56¹¹ and support the scenarios and malfunctions based on HFE V&V requirements of the Preliminary Safety Analysis Report (PSAR) for Shin-Kori Units 3&4. The HUPRESS was designed for the ISV in the advanced MCR of the APR1400 through reviews by SMEs, including one process expert and two human factors experts.
 - Configuration of HSIs. The HSIs of the APR1400 MCR are faithfully represented in the validation system, which is composed of LDPs, three operator workstations, and a safety console. It has flat panel displays (FPDs) for monitoring and/or controlling functions.

¹¹ American Nuclear Society Standards Committee, Nuclear Power Plant Simulators for Use in Operator Training and License Examination, ANSI/ANS 3.5, American Nuclear Society (1998).

- a. The LDPs support operators to monitor the plant status with dynamic information on the large plant system mimic panel. The LDPs continuously display spatially dedicated information that provides the status of the plant's critical safety functions, plant operation mode, key operating parameters and status, and trend displays. The LDPs provide two types of displays: (1) the fixed display, located at the center, enables the rapid assessment of plant conditions so that the personnel is able to quickly extract status information; and (2) the variable display provides the operator with flexibility in specifying LDP display information that supports varying information needs.
- b. The operator workstations consist of three areas: (1) the workstations for the reactor operator and turbine operator are located in front of each LDP (left and right side). The reactor operator and turbine operator information is displayed in LDPs, four information processing systems, and four Engineered Safety Features Component Control System (ESF-CCS) soft control modules; (2) the shift supervisor uses four information processing systems, four ESF-CCS soft control modules and two qualified indication and alarm system–non safety; (3) the shift technical advisor and the equipment operator use six information processing systems, six ESF-CCS soft control modules and two qualified indication and alarm system–non safety.
- c. The safety console provides the dedicated plant safe shutdown means separated from the operator workstation. It has the conventional operation and control means, however, the information is also displayed by flat panel displays.

- Configuration of HUPRESS. The HUPRESS involves the data acquisition from test facility, measurement of variables related to the performance of plant and personnel, and statistical analysis of the data, as described below in the functions of HUPRESS subsection. The HUPRESS includes an eye tracking system and an AV recording system. HUPRESS support human performance evaluation during HFE V&V, operator training, and operator qualification test by way of collection, reproduction, and analysis of plant/operator performance data including operator events, plant events, and audiovisual recording. Separate mobile evaluation stations and associated recording systems are provided for flexible use during the evaluation exercises. HUPRESS has the capability to archive and facilitate –through sorting and filtering of data– the retrieval of the evaluation data for the ISV exercises.

HUPRESS is interfaced with the APR1400 simulator and acquires the simulator logging data during a test. The logging data include the data representing the plant system events and status (e.g., status change of controlled components, alarms and flags, and process variables/parameters) and operator activities (display navigation, alarm control, soft control, and computerized procedure system control/navigation). Human performance is evaluated with the logging data by HUPRESS during the test, being also possible to reproduce the human factors validation tests process after the test. Also HUPRESS acquire the eye tracking data and process them into the measures for the situation awareness and the workload evaluations.

SMEs observe the operators' activities and check the activities related to the personnel task performance, the teamwork, and the anthropometric/physiological factors during the test. SMEs complete the evaluations of the personnel task performance and the BARS based on the observations after the test. The operators evaluate the KSAX and the NASA-TLX after the test.

The data observed and checked, evaluated, and recorded during the test can be further evaluated by time line analysis in an integrated way. In addition, HUPRESS has functions as various statistical analyses and reporting.

- Functions of HUPRESS. The functions of the HUPRESS are divided into the data

acquisition, the performance measurement, and the statistical analysis:

- a. Data acquisition. The HUPESS accumulates and stores the data related to plant performance and to personnel performance. For the plant performance, the system gathers real time data of all parameter and variables, and logs data about plant control and display management by operators. Then, the system stores the data in the data storage station. For personnel performance, the HUPESS accumulates the AV data, eye tracking data, expert evaluation results, and operator evaluation results.
- b. Performance measurement. HUPESS includes the performance measures of NUREG-0711. The six performance measures evaluated are plant performance, personnel task, situation awareness, workload, teamwork, and anthropometric and physiological factors.
 - Plant performance. The plant performance can be measured by monitoring, analyzing, and evaluating important process parameters. The data of the parameters can be obtained from log data of a simulator representing APR1400. Maximum or minimum values of the parameters at the end of scenario or during the scenario are used to evaluate the plant performance: whether the value of the parameter of interest exceeds the set-point value (or pre-defined value) or not. Time to complete the goal in a scenario is also used as a measure of plant performance. Discrepancy between ideal value evaluated in advance by experts and obtained value in the parameters of interest is used to score the operators' activities as crew performance.
 - Personnel task. Primary tasks, secondary tasks and the sequence of tasks are considered for the evaluation of personnel task. Optimal solutions to scenarios are developed by process experts through scenario analysis on the basis of top-down and bottom-up approaches. Check is made whether each activity in the optimal solution –in a hierarchical form– is satisfied or not. Hence weights of activities in personnel task can be easily obtained by using hierarchical techniques. Score on personnel task is evaluated with the weights. To measure the performance of primary tasks, three eye-tracking systems are used to investigate the information searching tasks of operators. For the performance of secondary tasks, HUPESS analyzes the log data on interface management.
 - Situation awareness. The modified subjective rating technique KSAX is used for the evaluation of SA. The KSAX is inexpensive, easy to use, and non-intrusive. The subjective measure is complemented by continuous measures based on eye tracking data, such as eye fixation in AOIs and the time spent by operators on visual examination of relevant system components during critical scenario time periods.
 - Workload. NASA-TLX and Modified Cooper-Harper are used to evaluate mental, physical, and temporal demand, self-estimated performance, effort, and frustration as workload. The subjective measures are complemented by continuous measures based on eye movements –blink rate, blink duration, blink interval time, eye fixation distribution on AOIs, fixation dwell time, or number of fixations.
 - Teamwork. BARS questionnaire is used to measure teamwork. BARS is composed of questions regarding task focus/decision-making, coordination, communication, openness, and team spirit.
 - Anthropometric and physiological factors. Concerns are given to visibility, audibility of indications, accessibility of control device, design and arrangement of equipment.

- c. Statistical analysis. The HUPRESS supports several statistical analyses of the performance data. The system provides the results of linear regression, ANOVA tests, correlation, t-test as well as mean values and variance.

Main results and conclusions

- Development of human performance measures for the ISV of the APR1400.
- Development of a human factors validation system facility, which includes HUPRESS, for the ISV of the APR1400.
- The HFE validation tests for Shin-Kori Units 3&4 HSI design are in progress using the human factors validation system facility. Also the full scope simulator model for the digitalized MCR of APR1400 is expected to be used for other validation processes.

Recommendations

- Specific recommendations on the application of the performance measures have already been included when describing the measures.

Further research

- On going project.

References

- Ha, J. S., Seong, P. H., Lee, M. S. and Hong, J. H. (2007). Development of human performance measures for human factors validation in the advanced MCR of APR-1400. *IEEE Transactions on Nuclear Science*, 54(6), 2687-2700.
- Kim, J. H., Ha, J. S., Ha, C. H., and Seong, P. H. (2004). Design of a human performance evaluation support system. The Seminar of JSPS-KOSEF Core University Program on Energy Science & Technology. Subtask CR04-2-2 “Advancement on Operation & Maintenance for Nuclear Power Plant”, November 1-2, 2004, Tohoku University, Sendai, Japan. http://sym-bio.jpn.org/old/reports/seminar/nikkanCUP/PDF/04_J.H.KIM.pdf
- Lee, M. S., Hong, J. H., Suh, J. K., Lee, S. H., Hwang, D. H. (2009). Development of human factors validation system for the advanced control room of APR1400. *Journal of Nuclear Science and Technology*, 46(1), 90–101.

Additional references:

- Ha, J. S., Seong, P. H. (2009). A human-machine interface evaluation method: A difficulty evaluation method in information searching (DEMIS). *Reliability Engineering and System Safety*, 94, 1557–1567.
- Ha, J. S., Seong, P. H. (2010). Attentional-resource effectiveness measures in monitoring and detection tasks in nuclear power plants. *IEEE Transactions on Systems, Man, and Cybernetics — Part A: Systems and Humans*, 40(5), 993-1008.
- Hong, J. H., Lee, M. S., Hwang, D. H. (2009). Computerized procedure system for the APR1400 simulator. *Nuclear Engineering and Design*, 239, 3092–3104.
- Lee, D. H., Jeong, C. H., Go, J. S. (2007). Regulatory issues of new control room design: a case study of Shin-Kori 3 and 4 nuclear power plants. In *Proceedings of the Workshop on Future Control Station Designs and Human Performance Issues in Nuclear Power Plants*. NEA/CSNI/R(2007)8. Paris, France: Organisation for Economic Co-operation and Development (OECD), pp. 447-460.
- Lee, D. H., Kim, D. I., Chung, C. H. (2007). Regulatory approach on human factors engineering of main control room modernization: a case of Kori-1 nuclear power plant in Korea. In *Proceedings of Joint 8th IEEE Human Factors and Power Plants (HFPP) / 13th Human Performance / Root Cause / Trending / Operating Experience / and Self Assessment (HPRCT)*, August 26-31, 2007, Monterey, California, USA.
- Lee, J. W., Oh, I. S., Cheon, S. W., Chung, Y. H., and Lee, J. H. (1999). Human factors

review guide for Korean next generation reactor. *Transactions of the 15th International Conference on Structural Mechanics in Reactor Technology (SMIRT-15)*, August 15-29, 1999, Seoul, Korea, XI-353 – XI-360.

7.4.CASE STUDY 4: HUMAN FACTORS V&V METHOD OF TECNATOM – SPAIN

| |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Study reference |
| Tecnatom. Human factors verification and validation in distinct NPPs. |
| Domain of origin |
| Nuclear power plant. |
| Type of study |
| Simulation. Performance based evaluation. The participants in the evaluations were end users: operators. When plant personnel were not available, instructors were involved. |
| Purpose of the study |
| Tecnatom started human factors engineering verification and validation (evaluation) of Spanish nuclear power plants by performing Detailed Control Room Design Reviews (DCRDRs) in the mid-eighties. The following V&V activities were related to new designs and plant modifications, according to the activities described in the HFE PRM, included in NUREG-0711. The Spanish nuclear regulatory body CSN recommends following the HFE PRM or an acceptable alternative method in the case of the HFE activities for new designs and design modifications. The activities of the HFE V&V process relate with Task Support Verification (TSV), HFE Design Verification (HFE DV) and Integrated System Validation in NPPs (such as José Cabrera, Almaraz, Vandellós, Beznau and an advanced NPP in Taiwan). |
| Theoretical underpinning |
| <ul style="list-style-type: none"> • The human performance model is based on operator actions with regard to monitoring and detection, situation assessment, response planning, response implementation, secondary tasks/usability, workload, situation awareness, communication and teamwork. • The HFE design and verification and validation processes were based on established guidelines, such as NUREG-0711, NUREG-0700, NUREG/CR-6393, INPO (NUTAC)¹², EPRI (2004), EPRI 101814¹³, ISO-9241 and ISO-11064. |
| Issues of integrated system validation |
| HFE V&V phases. Methods. Measures. Scenarios. Participants. Evaluation team. ISV reporting. |
| Validation stages |
| <ul style="list-style-type: none"> • Definition of verification and validation. V&V is an element of NUREG-0711, with the objective to help ensure that acceptable HFE practices and guidelines have been incorporated to applicant's HFE program for construction permits, operating licenses, standard design certifications, combined operating licenses and for license amendments, and not simply at the end of the design process as a V&V. • Overall evaluation process. The phases of V&V are according to NUREG-0711. |

¹² INPO (1983). *Component Verification and System Validation Guidelines* (INPO-83-047). NUTAC. INPO (1983). *Human Engineering Principles for Control Room Design Review* (INPO-83-036). NUTAC.

¹³ EPRI (1985). *Human Engineering Design Guidelines for Maintainability* (EPRI NP 4350). Palo Alto, CA: EPRI.

- Task Support Verification consists in checking that the HSI provides all alarms, information, and control capabilities required for personnel tasks.
- HFE Design Verification consists in checking that the characteristics of the HSI and the environment conform to HFE guidelines.
- Integrated system validation is an evaluation using performance-based tests to determine whether an integrated system design (hardware, software and personnel elements) meets performance requirements and acceptably supports safe operation of the plant.

Methods and measures

HFE V&V of Spanish control rooms NPPs started by performing DCRDRs –HFE Verifications– during the mid-eighties and ended at the early nineties. All MCRs of the Spanish NPPs were reviewed to find discrepancies HEDs –using Human System Interface Design Review Guideline (NUREG-0700 Rev. 0, 1981), INPO (NUTAC) and EPRI references– and the identified HED were solved. The DCRDR methodology included operating experience review, static verification of the MCR, operator response capability verification (availability and adequacy of the HSI components) and MCR validation. The general result was an improvement of HSIs as consequence of the review process.

After 1994, V&V activities were included as a part of the review areas, Element 10, of the HFE PRM (NUREG-0711). Spanish NPPs follow the NUREG-0711 approach for plant design modifications.

- Task Support Verification –TSV. Verification that the tasks defined in the tasks analyses can be performed with the designed HSI, i.e., the control and indicators included in each task analysis are available in the HSI, and that all HSI components are associated to a task.
 - Applicability. The TSV is needed, maybe except in modifications related to the replacement of equipment with the same functionalities, because HFE DV does not guarantee that a HSI is operable for the tasks to be performed.
 - Method selection. A task analysis was normally not required as an HFE activity in plant modifications in Spanish NPPs. When the task analysis was not available, the existing operating procedures or a review of the HSI by NPP operating department was used.
- HFE Design Verification –HFE DV. The HSI is analyzed in order to choose the applicable sections of the selected HFE guidelines. The HFE DV in Spanish NPPs has consisted on checking the characteristics of the HSI with the HFE guidelines of NUREG-0700, and in certain cases with ISO-11064, ISO-9241, EPRI 1008122 and EPRI 101814.
 - Applicability. HFE DV is always applicable when any HSI component is changed. A recommendation is the application of the HFE DV in HSI plant modifications related to safety systems and not related to safety systems.
 - Method selection. The method selected for the HFE DV depends on the HSI to be verified. If the HSI is small, one single HFE guidelines checklist can be used to verify the entire HSI, evaluating guideline by guideline each HSI component. However, if the HSI to verify is rather large, the HSI is divided into sections (panel sections, software systems, or groups of software displays), and, in new designs, the HSI is divided by facility, building, system, panel, group of displays, etc. In the final verification report, the results of the different filled-in checklists are grouped in a single checklist combining all results.
 - Human engineering discrepancies. The HFE guideline checklist can be fulfilled or not by the HSI. Not fulfilled guidelines should not always be considered a discrepancy that implies a later analysis and a design modification, as there can be a reasonable justification of the non-conformance. The possible answers to a checklist evaluation include “Yes”, “No, Discrepancy”, “N/A” and “Return”, using as a reference the table included in NUREG-0700 (Rev 1, Vol II) and being in compliance with HFE guidelines

of EPRI (2004).

- HSI verification of hardcopy design or an already built interface. Pros and cons: (1) The hardcopy HFE DV allows very easily design changes, with no great implications in costs and schedule modifications. However, the final HSI could have little in common with the initially verified HSI and, therefore, a final verification with the built design seems necessary (in compliance with Element 11 of NUREG-0711). (2) The HFE DV of an already built HSI has the advantage that the final appearance will not vary much from what has been reviewed, but the implementation of design changes can have a great impact on costs and schedule –in the case of software HSIs, design modifications may not be so difficult.

A HFE DV scheduled in different phases complies with NUREG-0711 –an iterative design process among the different elements of HFE PRM.

- Integrated System Validation –ISV. The most common method for a validation is to use a simulator, as the crew performance is observed when facing selected scenarios related to the modification, or representative of the whole plant operation in the case of a new design. Other methods, like walkthrough and talkthrough approaches, seem more appropriate to use in preliminary design stages of a HSI.
 - Applicability. An ISV focuses in issues not evaluated during the verification, and always applicable in a new design. For plant modifications, the applicability of the ISV depends on the type of modification. Performing ISV only for modifications related to safety systems could be too limited because non-validated modifications related to non-safety systems can change tasks, affect other HSIs or degrade operator performance.
 - Method. A variety of methods to observe crew performance and complete a validation exists (NUREG/CR-6393). In the ISV activities that are part of the licensing process, as well as part of Element 10 of the NUREG-0711, there are great limitations in budget, available crews and time to perform the validation, since the plant has to be in operation as soon as possible. The methodological approach was to perform scenarios that include several plant situations, without interruptions, as in the real operation. Each scenario was executed in a validation session model that includes the following activities: briefing, scenarios data collection, scenario preliminary analysis, questionnaire fill-in and interviews. However, the validation session model is adapted to the type of validation, as an example, in some cases the interviews and the questionnaires were carried out after the last scenario.
 - Measures. The observer team follow the crew actions during the scenarios, focusing on:
 - Monitoring and detection: operator capability to detect and monitor the information provided by the HSI.
 - Situation assessment: operator capability to interpret, diagnose and generate explanations regarding the status of the plant, using the information provided by the HSI.
 - Response planning: operator capability to decide the actions to take or the procedure to follow.
 - Response implementation: operator capability to perform necessary operating actions, following procedures and reference documents when using the HSI.
 - Secondary tasks/usability: operator capability to navigate through the HSI and access information and controls using the HSI. Ease to use the HSI.
 - Workload: the physical and cognitive demands placed on plant personnel Amount of tasks to be performed by an individual per unit of time or per scenario.
 - Situation awareness: the relationship between the operators' understanding of the plant condition and its actual condition at any given time.

- Communication and teamwork: operator's capability to communicate equipment and plant status to the crew members and work as a team with regard to cooperation, openness, adaptability, leadership and coordination.
- Participants. The validation plan depends on crew availability, simulator availability, time frame to perform the validation and scenarios to observe. Some examples of validations are the following:
 - One single crew during two weeks.
 - One crew per week, with a total number of crews between 4 and 7 (including a first week for a pilot validation).
 - Two crews during 1.5 weeks, one during the morning and one during the afternoon.

The number of crews varied, depending greatly on operators' availability. In the ISVs in Spanish NPPs, the crews ranged from three to six. Recommend that the participants in the validation are the end users of the HSI. When real crews were not available, instructors were used. Sometimes, all crews were available because the plant was under construction or the validation schedule allowed their participation.

For new designs, several V&V phases can be planned: the initial validation stages can be performed with non-real crews, while in subsequent phases, future crews should be the participants. With more crews, more data and variability of the collected data is obtained within the same scenario, although later hardly new things can be observed. Nevertheless, repetition of the same performance and absence of errors is a data that confirms the features of a good design.

- Training. The training is very important for the operating crews in order to use correctly the HSI, as well as for the observer's team.
 - Because of the time schedule, sometimes the ISV was performed during the crew training sessions, previously to the introduction of the design modification in the MCR. The advantages were that all crews were available, obvious design errors were detected and time was available to perform design modifications. But, hidden or difficult design issues were not detected. Without previous training, crews normally gain speed using the HSI when facing the scenarios. Therefore, a good practice is the alteration of the scenarios to be performed from one crew to another.
 - The training of the observer's team allows understanding the crew operating actions. Observers can anticipate what crews should do and know in-situ if it is done correctly.
- Scenarios. The number of scenarios depends on the HSI to be validated.
 - In a new design, all types of operational situations must be observed (normal, abnormal, transients and emergencies). Recommend an approach by shorter phases during the design process, with the advantage to find HEDs before the HSI is completed.
 - In design modifications, the scenarios should only be related to the modified HSI. The number of scenarios has varied from three to five, and each scenario is related to several plant situations that the crews must face. Up to five different plant situations, not sequentially linked, have been planned during a scenario.
- Data Collection. The data collection is performed by using blank pages or scripts describing the scenario –which are based in the operating procedures–. However, the scripts can be useless under an unplanned situation (different operating path) originated from operator actions and plant event dynamics. The data collected during the scenarios may be:
 - Annotations of the actions fulfilled (expected or not), time of the performed

actions, interfaces where the actions were performed, information exchanged, plant status, navigation path to access the desired information and HSI configuration. The annotations during the scenarios many times are limited to abnormal things because of little time.

- Summary of plant/simulator parameters (selected for each scenario).
- Performance measures depend on the observed situation. The measures can be time, accuracy, precision, frequency of performed actions, used resources, actions achieved or performed, communications, anthropometry and operator movements.
- Validation Analysis. The analysis has the following phases:
 - Analysis of each scenario and selection of HFE event/facts per scenario and per crew, in compliance with the issues to be tested.
 - Comparison and documentation of human factors event/facts per scenario and for all crews, in compliance with the issues to be tested.
 - Comparison and documentation of human factors event/facts for all scenarios and for all crews, in compliance with the issues to be tested.
 - Analysis of the fulfillment of acceptance criteria related to the HSI to be tested.
- Evaluation team. The observers' team during the data collection should be multidisciplinary, covering human factors expertise and plant operations.
- ISV report. The results of the validation process are presented in a summary report, including: objectives of the validation, brief description of the HSI, the validation method and the test conditions, the discussion of key findings based on the results, the discrepancies, and the conclusions and the recommendations. Also, the information generated in the validation analysis is included in the summary report as attachments to support the summary of findings and conclusions supplied in the main body of the document. The attachments include summaries of the scenarios and the relevant facts, analysis of each scenario and crew for the evaluated issues, analysis of each scenario with all the crews, joint analysis of all the scenarios and crews for the issues to be evaluated, analysis of questionnaires, and compliance with the acceptance criteria.

Main results and conclusions

- V&V activities covered task support verification, HFE design verification and integrated system validation in HSI design modifications introduced in several BWR and PWR Spanish Nuclear Power Plants (specifically ISV processes in José Cabrera NPP, Almaraz NPP and Vandellós NPP), in Beznau PWR NPP in Switzerland (the Westinghouse computer-based procedure system –COMPRO– and the Westinghouse alarm system –AWARE–), as well as in the design of a new advanced NPP in Taiwan.
- The evaluation method is being improved, in order to optimize the process and reduce execution time, during the successive V&V processes.
- Methodological aspects of the ISV are explained related to the number of crews, training, number of scenarios, issues to test, data collection and performance measures.
- Plan and integrate the evaluations activities from the beginning with the design activities and other NUREG-0711 review areas, always expecting a feedback from the V&V process. If a V&V is performed at the end of the design, the suggested modifications may not be incorporated, and also can be very costly and produce delays.

Recommendations

- V&V methodological recommendations have already been included in the section of methods and measures for TSV, HFE DV and ISV.
- Perform verification and validation, before the HSI is built, in several V&V phases:
 - Verification: before HSI is built employ the design document and when the HSI is being

| |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p>implemented, plan and allow the design modifications.</p> <ul style="list-style-type: none"> – Validation: walkthrough and talkthrough approach without simulator can be performed at the first design stages. Don't recommend performing a final validation before the HSI design is completed, as later the HSI design may change and, therefore, may incorporate not accepted HFE practices. For ISV planning, take into account the HSI definitive design and not only the plant outage when the modification will be implemented. |
| <p>Further research</p> <ul style="list-style-type: none"> • V&V activities are been carried out in modernization projects and in new HSI designs. |
| <p>References</p> <ul style="list-style-type: none"> – Trueba Alonso, P., Fernández Illobre, L., Jiménez Fernández-Sesma, A., Ortega Pascual, F. (2008). Human factors verification and validation: Tecnatom's experience. In <i>Proceedings of the 16th International Conference on Nuclear Engineering (ICONE16)</i>, May 11-15, 2008, Orlando, Florida, USA, pp. 209-216. – Trueba Alonso, P., Fernández Illobre, L., Jiménez Fernández-Sesma, A. (2008). Verificación y validación de factores humanos, su presencia como elemento 10 del NUREG-0711 y la experiencia de Tecnatom en su aplicación. In <i>Proceedings of 34th Reunión Anual de la Sociedad Nuclear Española (SNE)</i>, October 29-31, 2008, Murcia, Spain. <p>Additional references:</p> <ul style="list-style-type: none"> – Jiménez, A., Burillo, J. A. (2001). Verificación y validación de nuevos sistemas de apoyo a la operación para la C.N. Beznau / Verification and validation of new operation supports systems for Beznau NPP. <i>Nuclear España. Revista de la Sociedad Nuclear Española</i>, 206, 21-27. – Jiménez, A., Burillo, J. A. (2002). Verification and validation of new operation supports systems for Beznau NPP. <i>Nuclear España. Revista de la Sociedad Nuclear Española</i>, 215. |

7.5.CASE STUDY 5: TWICE INTEGRATED HSI VALIDATION OF RINGHALS UNIT 2 – SWEDEN

| |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p>Study reference</p> <p>Westinghouse and Ringhals NPP. TWICE integrated HSI validation of the main control room of Ringhals Unit 2</p> |
| <p>Domain of origin</p> <p>Nuclear power plant.</p> |
| <p>Type of study</p> <p>Simulation. Experimental methods. Test crews of operators. Validation of final design solution of a fully modernized control room. The data collection of the integrated validation took place from December 2008 to January 2009.</p> |
| <p>Purpose of the study</p> <p>I&C modernization project for the main control room of PWR Ringhals Unit 2 NPP (Sweden) carried a large number of changes to the MCR HSI. The modernization project (referred to as the TWICE project: Ringhals TWo Instrumentation and Control Exchange) replaced all control boards and desks, as well as all associated indicators and controls. The integrated validation was required to ensure that the newly designed control room operated as well as or better than the existing control room.</p> |

The reference measurement of the existing control room (tests of the MCR assessment) was carried out in the fall of 2000. The MCR ensemble –comprising the MCR HSI, the training program, and the procedures– was the subject of the integrated validation. The integrated validation tests were conducted over four weeks.

Theoretical underpinning

- The control room should support operators: detecting plant parameters that indicate a problem or change in plant state that requires attention; diagnosing the problem based on indications; and taking correct actions in a timely manner.
- The guidance for ISV was NUREG-0711, NUREG-0700 (Rev. 1), NUREG/CR-6393, ISO 11064 and Ringhals Instruktion 1738 Handbook.

Issues of integrated system validation

One step upgrading. Benchmark validation. Measures. Participants. Evaluation team. Performance criteria: requirements, benchmark and expert judgment-based.

Validation stages

- Definition of ISV. “(...) an evaluation using performance-based tests to determine whether an integrated system design meets performance requirements and acceptably supports the safe operation of the plant.” (NUREG-0700, Rev. 2).
- Validation process. The validation of the MCR was carried in two main stages, the MCR assessment (of the old control room) and the integrated validation (of the modernized control room).

- 1) MCR assessment. The objectives of the MCR assessment were to establish a baseline level of performance of the existing Ringhals Unit 2 MCR and to develop acceptance criteria to be used for comparison to the performance of the modernized MCR.

Five crews (each composed of four members: shift supervisor, reactor operator, assistant reactor operator and turbine operator) from the plant being upgraded completed one week of testing on the high fidelity Ringhals 2 simulator. The five crews performed ten scenarios that represented a range of plant conditions. All scenarios were considered difficult, with some scenarios being more challenging than others.

Three observers –two operations experts and one human factors specialist– recorded data about operator performance during the scenarios and subjectively rated operators’ performance and teamwork.

The baseline study collected cognitive and team process measures as well as outcome measures of performance to establish benchmark values to use in developing acceptance criteria for the integrated validation of the modernized control room.

The MCR assessment measures were:

- Workload (self-rated, observer-rated and NASA-TLX).
- Teamwork (self-rated and observer-rated).
- Situation awareness (self-rated, direct-query and observer-rated).
- Target events (observer-logged).
- Errors (observer-logged).
- Critical human actions (observer-logged).
- Qualitative (questionnaire-based and observer-logged).

Empirical evidence was established for a relationship between process measures of performance (i.e., detection of target events, diagnoses, measures of workload, teamwork and situation awareness) and operationally significant outcome measures of performance.

- 2) Integrated validation. The integrated validation compared the performance of the new

MCR ensemble to benchmark values of performance measured in the existing MCR, which were obtained from an assessment of performance (the MCR assessment benchmark test) using the existing MCR ensemble design.

The objective of the integrated validation was to show that the MCR ensemble was as good or better than the existing MCR ensemble, allowed to meet the plant safety objectives, the operators maintained acceptable workload levels, supported situational awareness, and provided the capability for error avoidance, detection and/or recovery.

Methods and measures

The new Ringhals Unit 2 MCR had the same general layout and set of controls and indications. All control boards and consoles were redesigned and replaced with a combination of dedicated (conventional) indications and controls as well as Video Display Unit (VDU)-based displays that contain indications and controls on soft displays, implemented as part of a Distributed Computer System (DCS). Large screen VDU-based displays (a combination of trends and plant process-related displays) presented overview information of the primary side of the plant, the secondary side and the electrical system. Alarms were indicated by an alarm presentation system (APS), which presents functional groups of alarms. The new system turbine automatic controls turbine plant start-up, monitoring, and shutdown operations.

The configuration of the Ringhals Unit 2 crew structure was not modified –a shift supervisor, a reactor operator, an assistant reactor operator and a turbine operator.

- **Methods.** The methods used to prepare for the integrated validation included scheduling the test observers and simulator, reviewing the test scenarios, preparing for data analysis and a one-week test run (or “dress rehearsal”).
- **Measures.** The measures of performance included both outcome measures (objective actions taken by operators that directly impact the plant) and process measures (cognitive and team processes that affect outcome performance). The integrated validation measures were benchmark-based, requirements-based and expert judgment-based.
 - 1) **Benchmark-based:**
 - Detection and diagnosis (observer-logged).
 - Teamwork (self-rated and observer-rated).
 - Situation awareness (self-rated and observer-rated).
 - Workload (self-rated, observer-rated and NASA-TLX).
 - 2) **Requirements-based:**
 - Critical human actions (observer-logged).
 - Plant parameters: core exit thermocouple temperature, containment pressure, reactor coolant system (RCS) pressure and steam generator power-operated relief valve (SG PORV) (observer-logged and simulator trends).
 - 3) **Expert judgment-based:** operations and human factors expert observation and questionnaires.
- **Participants.** Four test crews participated in the integrated validation. Initially five crews (same number of crews who participated in the MCR assessment) were defined in the validation test plan, but constraints related to Ringhals NPP allowed four operating crews.
- **Training.** The operating crews that participated in the integrated validation had a uniform amount of training (five weeks of simulator training prior to the validation) as well as all crews completed their last week of pre-validation training seven weeks prior to beginning the integrated validation test.

Additionally, the operators will receive more training between the end of the integrated validation and the startup of the new plant.
- **Scenarios.** The scenarios covered a broad and representative set of plant conditions as well as included situations identified as critical human actions and as historically difficult for the

operators to perform. The scenarios of integrated validation were the same of the MCR assessment; further, a simulator instructor, operations expert and I&C engineers identified some modifications on scenario aspects to account for changes to the HSI or I&C system of the modernized MCR ensemble.

Nevertheless, as more than eight years elapsed between the MCR assessment and the integrated validation, the experimenters didn't consider the scenarios learning effect as a concern (the participants could recall details of the scenarios that would give them an advantage).

- Test observers. Experts in plant operations and human factors observed the scenarios. Two types of observers participated in the integrated validation:
 - Data-logging observers. Three data-logging observers monitored the scenarios, logged the operators' actions, and rated the teamwork. One observer from Westinghouse participated in all four weeks of testing, while three operations experts from Ringhals NPP rotated to fill two of the observer positions. All observers had also participated in the MCR Assessment.
 - Expert observer team. Four expert observers carried out a qualitative assessment of the performance of the MCR Ensemble that was used to supplement the more quantitative findings of the validation. The members of the expert observer team were an operations expert from Westinghouse, a human factors expert from Westinghouse, an operations/human performance expert from Ringhals NPP, and the fourth member was a collection of comments from the seven Ringhals 2 shift supervisors, after they had completed a training course on the new MCR Ensemble.
Immediately following the completion of the integrated validation, the expert observer team emitted a report to provide feedback on the adequacy of the MCR Ensemble and as supplemental information for the final validation report.
- Data processing. The data processing largely consisted of comparisons with the baseline data already collected during the MCR Assessment. Spreadsheets to compare the integrated validation data with the baseline data were constructed prior to testing. This allowed on-line entering of the generated validation data.
- Pilot test for the integrated validation. The pilot test was conducted approximately one month before the start of the integrated validation. The dress rehearsal was performed to examine the small adjustments that were made to the scenarios, and to re-familiarize the test administrators and observers with the methods and measures of the validation.
- Performance criteria. The criteria for the acceptance of the new MCR Ensemble were established in the integrated HSI validation test plan.

Main results

- 1) The MCR ensemble satisfied the acceptance criteria. A summary of general results:
 - Plant safety was maintained throughout the validation (per requirements, performance and expert judgment).
 - Requirement-based measures of performance satisfied acceptance criteria (critical human actions and plant parameters).
 - Detection and diagnosis supported by new MCR Ensemble as well as the current MCR Ensemble.
 - All objective and performance-based measures satisfied the acceptance criteria.
 - All subjective ratings (observer and operator) satisfied acceptance criteria (except for 3):
 - a. Self-rated performance, frustration and temporal demand likely resulted from unfamiliarity and alarm issues.
 - b. Did not affect performance or safety. Does not invalidate MCR Ensemble.
 - c. Continue to monitor after further operator training and alarm system refinements:

Rerun one scenario and collect rating data to analyze.

- 2) Results on the requirements-based criteria:
 - Critical human actions:
 - a. Were performed successfully, with two exceptions:
 - i. An automatic actuation solved a primary system dilution problem before the operators had a chance to address it themselves.
 - ii. For a scenario with consecutive Steam Generator Tube Ruptures (SGTRs) (beyond design basis), one crew diagnosed the first SGTR, but did not have time to diagnose the second SGTR before the scenario had to end (time constraint).
 - b. Satisfied the acceptance criteria:
 - i. Neither issue compromised the safety of the plant.
 - ii. Validated the robust nature of the MCR Ensemble.
 - iii. 3 of 4 crews successfully performed a scenario beyond design basis, and the fourth likely would have if given enough time.
 - Critical plant parameters: their limits were not challenged at any time, which satisfied the acceptance criteria:
 - a. Core exit thermocouple temperature < 1093 °C.
 - b. Containment pressure < 3.5 bar.
 - c. RCS pressure < 188.5 bar.
 - d. SG PORV –Significant radiation not released to environment.
- 3) Results on the benchmark-based criteria:
 - Detection and Diagnosis (event count data):
 - a. Results between baseline and validation virtually identical, regarding counts of target events, diagnoses, actions and alerts.
 - Teamwork (observer and operator-rated):
 - a. All results equivalent, with no significant differences.
 - Situation awareness (operator rated and observer logged):
 - a. All results equivalent, with no significant differences.
 - b. No observer comments to suggest a significant problem.
 - Workload (NASA TLX):
 - a. 5 of 8 results equivalent, with no significant differences.
 - b. Self-rated performance and frustration, 2 of 8 results failed to show equivalence, but were not significantly different. Both will improve with increased familiarity.
 - c. Temporal demand result failed to show equivalence and was significantly different. Will improve with familiarity, but should be monitored.
 - d. Diagnostic data results and comments suggest that these results can be attributed to unfamiliarity issues, and an alarm system issue that was corrected.

Recommendations

- For executing an integrated validation, many issues need to be considered, such as scheduling the time of the operating crews, scheduling simulator time, reviewing the test methods and procedures, and planning and preparing for data processing.
- The integrated validation may serve as assistance to others who are planning to execute a validation test of a similar nature.
- After more familiarity gained on the HSI and the alarm system modifications were implemented, rerunning one scenario (with highest workload ratings) was recommended for collecting and analyzing workload data.

Further research

N/A.

References

- Forsberg, M. (2004). The Ringhals HSI and control room modernisation programme – Lessons learned. The practical application of a contemporary user and HF based HSI design process. In *Proceedings of the Man-Technology-Organisation of the Enlarged Halden Programme Group Meeting (EHPG)*, May 9-14, 2004, Sandefjord, Norway.
- Lang, A. (2007). Validation plans for a modernized main control room. In *Proceedings of IAEA Technical Meeting on Integrating Analog and Digital Instrumentation and Control Systems in Hybrid Main Control Rooms at Nuclear Power Plants*, October 29 - November 2, 2007, Toronto, Ontario, Canada.
http://entrac.iaea.org/I-and-C/TM_TORONTO_2007/Presentations/3A-TUESDAY_9-16_19-21_31/21-LANG-PRESENTATION%2021-%20Validation%20Plans%20for%20a%20Modernized%20%20.ppt#326,1,
- Lang, A. (2010). TWICE Integrated HSI validation. In Braarud, P. Ø., Nystad, E., Strand, S., Skråning, G., Bye, A., Hildebrandt, M., and Massaiu, S. (2010). *The Halden Reactor Project Meeting on Integrated System Validation (ISV) – Status of Current Approaches to ISV and R&D Needs (HWR-939)*. Halden, Norway: OECD Halden Reactor Project.
- Lang, A. W. (2009). Preparing for the validation of a modernized main control room. In *Proceedings of the Sixth American Nuclear Society International Topical Meeting on Nuclear Plant, Instrumentation, Control and Human-Machine Interface Technologies (NPICT&HMIT)*, April 5-9, 2009, Knoxville, Tennessee, USA, pp 2402-2407.
- Lang, A. W., Roth, E. M., Bladh, K., Hine, R. (2002). Using a benchmark-referenced approach for validating a power plant control room: results of the baseline study. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 5, pp. 1878-1882.

7.6.CASE STUDY 6: INTEGRATED SYSTEM VALIDATION OF CONTROL ROOM OF OSKARSHAMN UNIT 1 – SWEDEN

| |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Study reference |
| IFE and Oskarshamn NPP. Human factors verification and validation of Oskarshamn NPP Unit 1 (a-b-c benchmark validation). |
| Domain of origin |
| Nuclear power plant. |
| Type of study |
| Simulation. Performance based evaluation. The participants were operating crews of Oskarshamn NPP Unit 1 (OKG1). The modernization of OKG1 followed one step approach. The ISV employed a phased approach, with the data collection being carried out in two OKG1 control room simulators. One simulator served for obtaining the baseline of the human performance in the control room (1999), while the new simulator was employed for the data collections in 2002 (before the start up of the plant) and in 2005 (after more than 2 years of operation). Therefore, the performance of the new control room was measured two times: in 2002 and in 2005. |
| Purpose of the study |
| Oskarshamn 1 BWR NPP has been in operation since 1972. New safety requirements for design |

changes in the process systems and instrumentation, as well as shortcomings in the control room due to many previously performed modifications, led, in addition to several plant modifications, to the decision of building a new hybrid screen-based control room, located in the same space as the old one, and with the same number of operators. The control room upgrade was in one big step. The modernized plant was operational in January 2003.

The human factors verification and validation plan included the benchmark validation approach, for testing the new control room against the old control room by comparing human performance in the new simulator to human performance in the old simulator. The acceptance criteria was that human performance in the new control room should be at least as good as in the old control room.

Theoretical underpinning

- The HFE design and verification and validation processes of the OKG1 control room was based on established guidelines, such as ISO 11064, NUREG-0700, NUREG-0711 and NUREG/CR-6393.

Issues of integrated system validation

HFE V&V plan. One step upgrading. Benchmark validation. Measures. Scenarios. Participants. Evaluation team. Acceptance criterion.

Validation stages

- Definition of verification and validation.
 - Verification involves checking that specifications are met and factored into designs.
 - Validation involves testing that the design adequately supports safe and efficient plant operation.
- Pre-studies. In 1994, when the new technology (screen-based operator interfaces and digital control systems) started to be introduced into nuclear power plants, OKG (*Oskarshamn Kraftgrupp*) initiated a pre-study –called Project KRUM– of how the new technology should be applied and implemented in the plant design. A new concept of operations, requirements on the design of system and operator interfaces, implementation strategies, new design processes, methodologies for training operators and I&C technicians, and an approach to verification and validation were developed. Special attention was paid to operators’ involvement during the entire design process, including HFE V&V, defining requirements for education and training, and ISV in the full scope simulator before implementation in the plant.
- Overall plan for validation of the final design.
 - The human factors verification and validation plan contained a full-scale ISV of the control room. The approach for the validation was to compare the human performance of the new control room to the human performance of the old control room, utilizing the full-scale training simulator. The acceptance criterion for the new control room was that human performance in the new control room should be at least as good as in the old control room.
 - The human factors verification and validation plan described the approach as an “a-b-c” design, “a” denoted the measurement in the old control room (baseline for comparing the new control room against), “b” signified the measurement of the new control room before actual operation, and “c” indicated the measurement of the new control room after some period of actual operation. The phase “c” had the purpose of getting a measurement more comparable to the old control room than the phase “b” in terms of training level, experience and practice with the control room, the work routines and the way of using the new human-machine interface.
 - The baseline “a” was performed in 1999. The data collection of “b” was performed

during 2002 before the start-up. In spring 2002, the comparison of the human performance measured in “b” against the baseline “a”, which was made before completing operator training, indicated that the crew’s plant performance was satisfactory in the new control room, and that the workload and task complexity were experienced as being similar. However, there were some concerns about slightly reduced task performance and situation awareness. In the autumn of 2002, a second test (follow-up validation) of the new control room was also performed with three crews. The result of the second test was comparable to performance level of the old control room. The data collection for the “c” part was performed in March and April 2005.

Methods and measures

The new control room design was a unified interface screen-based, the backup in conventional technology in a safety panel and a safety desk. The overview information was presented on large screen and conventional equipment.

The control room design process followed the program review model of NUREG-0711 with the four general activities (planning and analysis, design, verification and validation, implementation and operation) and the related elements. It has proven to be of high importance to have an accepted and traceable design process.

- The design team developed the features of the new control room. OKG1 was leading the design team, and was responsible for all requirements regarding HFE V&V and training. The contractor on HFE V&V was IFE.
- Verification and validation plan. The V&V overall plan described: (1) basis: methods, personnel, documentation, analysis and follow up; (2) identification of the operator tasks (procedures, PRA/HRA analyses), V&V of single system (control room layout, large screen, safety panel, operator station, alarm system, control room suite and ECR); (3) V&V of the subsystem: safety panel, operator station and large screen together with procedures; and (4) verification and integrated validation in full scale simulator.

The V&V plan stated that a good validation design was to measure the new control room before deciding about start-up of the plant and after the new control room had been in actual operation for some time

- Methods: Benchmark. The human factors V&V plan for the modernized control room included comparing the human performance of the new control room to the old control room. The acceptance criterion was that the new control room should be at least as good as the old control room.
- Measures. The types of human performance measures consisted of plant performance (measurement of the deviations from predefined ideal process values), task performance, cognitive factors (situation awareness, workload and task complexity), and work process (quality of teamwork).
 - Background questionnaire: assessed operator’s age, technical education, experience in the crew and operator position in the control room.
 - Operator Performance Assessment System (OPAS): provides a task-goal oriented performance score. A process expert analyzed beforehand what activities needed to be performed (information gathering/observation, and intervening actions on the process) in order to complete the scenario successfully. The observed activities according to their weighted importance resulted in a score, which indicated how many of the defined activities the crew performed relative to the optimal solution. A process expert performed the OPAS scoring in real-time during the scenarios.
 - Operator response time: measured as the time interval elapsed between a specific event from the process (e.g., an alarm or a process event) and a specific operators’ response. The events and responses were recorded by the experimental logging systems during the

experiment, noted by an observer during the scenario, or observed from the video recordings of the scenario.

- Observer rated performance: the process expert and the instructor rated the crew's performance after each scenario. The rating scale covered the crew's information gathering, prediction of the process development, understanding of the process status, task performance, and the process condition resulting from the crew's operation.
 - Observer rated teamwork: a seven item rating scale was composed of planning, use of procedures, communication of process information, crew discussion of status and plans, occurrence of risky actions, evaluation of status and plans and positive spirit.
 - Crew plant performance: plant parameters selected to give indications on the quality of crew performance.
 - Situation Awareness Control Room Inventory (SACRI): measures the operators' knowledge of the current, past and future state of certain plant parameters. Questions were asked regarding the state of a number of parameters, and the operators answered whether the level of the parameter had increased, decreased or were the same. The SACRI questionnaire was administered in each scenario break, and six questions about the state of one plant parameter for each of the time periods present, past and future were asked.
 - Operator's self-rated performance: the operators rated their own perception of the crew's performance on a three item rating scale, which covered cooperation within the team, the performance on the crew's tasks, and the development of the plant process.
 - Operator's self-rated complexity: the operator's perception of the complexity of the scenario based on his experience of running the given scenario was evaluated using a rating scale.
 - Operator' self-rated workload with NASA TLX: consists of the six subscales: mental demand, physical demand, temporal demand, performance, effort and frustration.
 - Operator's self-rated situation awareness. A three item questionnaire assessed the operator's own experience of overview of the process status and process development in the scenarios. The three items covered the operator's information gathering relevant to the process, understanding of the process status, and the predictability of the process development.
 - Usability assessment of the new simulator's Human-Machine Interface (HMI): the operators made an assessment of the usability of the new HMI after completing the five scenarios in the new simulator. Each operator evaluated the HSI on a twenty item rating questionnaire (with a seven point scale) that also included open questions for comments. Sixteen items were about acceptability of the interface and four items contained a comparison of the new and the old control room interfaces.
- Experimental design. The validation design was a 3x4 factorial design, with the independent variables being the control room (3 tests) and the scenarios (4 scenarios). The control room consists of three levels: the old simulator measured once and the new simulator measured twice. The same training scenario and the four main scenarios were used in all three tests. The main scenarios were presented in a balanced order with a Latin Square design. The dependent variables were assessed by means of operator questionnaires, observations by process experts or examination of logs and video recordings from the test.
 - Test-beds. The tools employed for design and V&V comprised virtual reality model, workstations, part simulator and full scale simulator. Two simulators were employed as test-beds during the ISV of OKG1. The KSU (*Kärnkraftsäkerhet och Utbildning AB*) was the responsible owner of the simulators.
 - The simulator of the OKG1 control room used before the modernization process for

training purposes since the early nineties and located in Studsvik, was referred as the old OKG1 simulator and served for the baseline data.

- The new OKG1 simulator, developed during the modernization process and located in Oskarshamn, served as the test-bed for the two tests of the new control room. The new OKG1 simulator was used for full-scale training on normal, disturbed and emergency operation in advance to the first test in the new control room performed in April to May 2002. Between the test in April/May 2002 and the follow up test in September 2002, the simulator was updated including the process formats, the alarm logic formats or all CR procedures. Between the 2002 and the 2005 tests the new OKG1 simulator was completed according to the original design specifications and also was adjusted following changes performed to the plant after 2002 (including for example improved alarm system features or updated process formats).
- Participants. Operators of the OKG1 control room participated in the validation. Eight crews participated in all the three tests “a”, “b”, and “c”.
- Training. The operators’ general training level on the old simulator was good. For the 2002 test, the operators’ training on the new simulator consisted first of theoretical education on the new plant and interface during 2001 and early 2002. Afterwards, operators participated in two weeks of full-scale simulator training, on both normal operation and disturbed operation. For the 2005 test, the operators had more than two years of experience from the actual control room. Also the operators’ education and training were complemented with training on the new procedures, on the new way of working in the control room, and the regular/ordinary simulator training sessions of 2003 and 2004.
- Scenarios. The selected set of operational scenarios for the various validation tests were based on the sampling dimensions for scenarios recommended in NUREG/CR-6393. The scenarios contained accident (reactor scram) and non-accident operation, tasks that required the use of interfaces and process systems that were planned and not planned to be modernized. The scenarios included procedure guided and non-procedure guided operation. These requirements were implemented in four main scenarios consisting of sixteen scenario tasks. In addition the validation included one introductory scenario containing three scenario tasks.
- Pilot tests. Before the tests in both simulators, a pilot test was performed with one control room crew to test the simulator, the data collection methods and the scenarios.
- Data collection: experimental staff and test procedure.
 - The experimental staff consisted of an experimental leader from IFE, an instructor and a process expert both from KSU. During the validation tests, each member had specific tasks to perform including briefing, debriefing, simulator set-up, administration of data collection procedures, and role-play of relevant plant staff during the simulations. To assure comparable conditions for all crews, written procedures were used for the staff tasks.
 - The procedure was the same for the tests in the old and the new simulators for all crews. The subjects were given a briefing prior to the benchmark tests, and then followed the actual simulator scenarios and data collection.
 - a. Briefing. Prior to the benchmark tests, the participants were informed of the purpose of the test. They were given general information about the data collection procedure and that the findings could not be traced back to the individual participants.
 - b. Technical preparations were carried out before the data collection started (such as the video recorders, the audio recorders, the microphones and the logging of simulator data from the simulator).
 - c. Prior to the tests, each operator answered a background questionnaire and a process

expert and an instructor made an assessment of the complexity of the scenarios.

- d. During the scenarios, a process expert and a training instructor made observations and ratings of the crews' performance. Questionnaires were administered to the operators in scenario brakes.
 - e. Some dependent variables were assessed after the benchmark test through examination of the data logs or video recordings from the test.
- Video and audio recording and simulator logs.
 - Video and audio recording. The experiment was recorded by four video cameras: two directed towards the primary operating area (providing an overview of the CR) and two recorded panels in the secondary operating area of the control room. Pan and zoom camera features were available. In the observer's gallery, three video monitors showed the primary operating area overview picture, the zoom camera, and the secondary operating area. The audio was recorded from each operator by wireless microphones, and a wired headset also recorded sound from the process expert and gave the process expert a mix from the microphones of the operators.
 - Simulator logging. The full-scale integrated validation logged data from the simulator during each run of scenarios in both the old and in the new control room. Two types of data were logged: the development of a selected set of process parameters and component events during the scenario. The process parameters were selected by a process expert to cover the important aspects of the development of all five scenarios used. The events logged during the scenarios were the event list generated by the simulator for presentation to the operating crew.
 - Acceptance criteria for the human performance of the new control room. The acceptance criterion was that the new control room should be at least as good as the old control room. The acceptance criteria for the full-scale benchmark test considered the importance of the different types of measures and the type of analysis to be used as basis for deciding on acceptable performance of the new control room.
 - The initial criteria established that the performance measures "crew plant performance" and "OPAS task performance" indicated acceptance of the new control room, while the remaining measures –situation awareness, workload and work process measures– had to be interpreted within the overall results of the validation. However, strongest weight was on the OPAS task performance measure as acceptance criteria, as it was difficult to establish a crew plant performance measure across the three control room tests.
 - Statistical significance (with ANOVA) and practical significance investigated if the new control room differed from the old control room. Systematic patterns of the effects of the control room on several performance measures were investigated searching for convergent validity of the performance of the new control room.

Main results and conclusions

- The validation test utilized a large set of performance measures, and performed three comprehensive full-scale simulator data collections involving all control room crews of the plant.
- The analysis of the statistical power as well as the results pointed to sufficient statistical power and performance measure that captured the effects of changes to the control room configuration.
- Similar results from both the global statistical analyses of performance measures and the results from detailed analysis of the individual tasks clearly showed that the new control room was at least as good as the old control room. In addition, there were coherent indications of the human performance of the new control room being slightly better than the human performance of the old control room for the accident type of scenarios.

- Results based on the operators opinion indicated:
 - Quite easy to operate in the new control room.
 - Large screen: share information to the whole team.
 - Operator station: good navigation and good control.
 - Safety panel: good overview.
 - Good control room layout and work places.
- Results pointed to some areas of improvements in the alarm system, because of: (1) not motivated alarm, during operation test and disturbance; (2) not understandable alarm; (3) difficult to separate different alarm priorities due to alarm horns; (4) impossible to block alarm; and (5) event list too detailed. The main problems in the alarm system –difficulty to separate different alarm priorities due to alarm horns and the blocking of alarms during outage and service– were solved during outage 2004.
- It may be difficult to identify the causes of poor performance, the results from ISV can be hard to understand and interpret, and often have to use comments from operators to identify the problem.
- Lessons learned from OKG1 were employed for the modernization project of Oskarshamn NPP Unit 2 (OKG2) control room. The control room modernization OKG1 showed that:
 - The involvement of the end-users (operators) and human factors expertise in the overall control room design process ensured human-centred solutions (high usability), and led to a high operator acceptance level.
 - The integration of V&V activities from the very start ensured a design process in which design flaws were discovered early, reducing the probability of expensive and troublesome issues at later stages in the process, and enhancing quality.
 - Close cooperation with the regulatory authorities was considered important. Open dialogue and early information transfer will ensure that the authorities can make a proper evaluation of the project and suggest modifications, and will lessen the time needed for the licensing process. The plant and the authorities have the same goal: to achieve the best possible control room in a structured way.
 - Responsibility for HFE work was a hard work for the OKG organization and complex regarding responsibilities and logistics.
 - Apply lessons learned from the Oskarshamn Unit 1 modernization and use resources from Unit 1 to support the Unit 2 work.
 - One step upgrading was too much work and required a long outage. Therefore, the modernization of Unit 2 was stepwise, with the focus on one major plant area/work place (reactor/turbine) in each step. Starting with operational, non-safety related I&C and later to continue with the safety I&C in order to promote a gradual learning and understanding of the new technology and the new way of working for the operating crews and maintenance staff.

Recommendations

- Proposal for improvement:
 - Validation if the way of working is suitable for modernized MCR.
 - Integrate workload and staffing factors in ISV.
 - How to validate not simulated plant mode (i.e., outage).
- Perform an ISV for all large modification (e.g., major interface modifications or new ways of operating major components). After all larger modification in MCR, ISV has to be performed in full scale simulator, to ensure and prove that the control room modification is as least as good as the old one.
- Several recommendations have been included in the lesson learned of the results and

| |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| conclusion characteristic. |
| Further research |
| <ul style="list-style-type: none"> • The modernized OKG1 plant was operational in January 2003. The lessons learned of the HFE V&V process are being used for the modernization process of OKG2 (Plant Life EXTension or PLEX project) and OKG3 (Power Up-rate with Licensed Safety or PULS project). |
| References |
| <ul style="list-style-type: none"> – Braarud, P.Ø. and Andresen, G. (2005). <i>The a-b-c benchmark validation of the upgraded Oskarshamn 1 control room</i>. IFE/HR/F-2005/1275. Halden, Norway: Institute for Energy Technology. Confidential. – Gunnarsson, T. (2007). Experiences from integrated system validation in OKG. In Braarud, P. Ø., Nystad, E., Strand, S., Skråning, G., Bye, A., Hildebrandt, M., and Massaiu, S. (2010). <i>The Halden Reactor Project Meeting on Integrated System Validation (ISV) – Status of Current Approaches to ISV and R&D Needs (HWR-939)</i>. Halden, Norway: OECD Halden Reactor Project. – Gunnarsson, T. (2007). Modernizing of Oskarshamn NPP with focus on control room issues. In <i>Proceedings of IAEA Technical Meeting on Integrating Analog and Digital Instrumentation and Control Systems in Hybrid Main Control Rooms at Nuclear Power Plants</i>, October 29 – November 2, 2007, Toronto, Ontario, Canada. – Gunnarsson, T. and Farbrot, J. E. (2005). Integrating the human factor in the modernization of Oskarshamn 1. <i>Eurosafe Tribune</i>, 15-17. – Gunnarsson, T., Eliasson, M. (2010). The control room upgrade in Oskarshamn 2 modernization project, lesson learned from on going human factor design process. In <i>Proceedings of the Seventh International Topical Meeting on Nuclear Plant Instrumentation, Control and Human Machine Interface Technologies (NPIC&HMIT)</i>, November 7-11, 2010, Las Vegas, Nevada, USA, pp. 1812-1821. – Gunnarsson, T., Eliasson, M. (2011). The control room upgrade in Oskarshamn 2 modernization project lesson learned from ongoing human factor design. In <i>Proceedings of the Man-Technology-Organisation of the Enlarged Halden Programme Group Meeting (EHPG)</i>, October 2-7, 2011, Sandefjord, Norway. |

7.7.CASE STUDY 7: HUMAN FACTORS V&V OF CONTROL ROOM OF OSKARSHAMN UNIT 2 – SWEDEN

| |
|------------------------------------------------------------------------------------------------------------------------------------------------------|
| Study reference |
| AREVA NP and Oskarshamn NPP. Human factors verification and validation of Oskarshamn NPP Unit 2: Plant Life Extension (PLEX) Project ¹⁴ . |
| Domain of origin |
| Nuclear power plant. |
| Type of study |
| Simulation. Performance based evaluation. For the control room design and HFE work, experienced current and ex-operators, who have |

¹⁴ The engineering, construction, and equipment supply is being performed by the Consortium of PLEX (COP). COP consists of a partnership of AREVA NP GmbH, Siemens, and Heidkamp. AREVA NP is the lead organization and is responsible for the HFE work and the control room modernization.

also been involved in other modernization projects at both OKG Units 1 and 2, participated with the COP HFE and control room design personnel.

The modernization of the plant was a stepwise approach and based on the gradually introduced modern technology in the MCR. The ISV phase approach consisted of the first base line obtained in 2005 and the human factors validation in 2007 and 2008. Another base line was obtained in 2010 and a new ISV to be performed in 2011.

Purpose of the study

Oskarshamn 2 BWR NPP (a 600 MW ABB Atom) has been in operation since 1975. Modernization and power up rate of the OKG facilities is being carried out since middle 1990's. The modernization project of OKG2 is stepwise and is referred as PLEX project. The scope is to make the changes required by the new safety requirements, apply for a thirty year license extension –the license to operate OKG2 expires in 2012–, and to concurrently make changes for a major power up rate. Project PLEX requires compliance with the requirements of the Swedish Radiation Safety Authority (SSM).

In the first step all I&C and control equipment for the turbine is changed to digital equipment. Nearly half of the control room equipment is changed to modern technology as operator stations for information and control and large screens for overview information. Second step of upgrading of OKG2 is to improve the safety in the plant and change I&C and control room equipment for these functions. In the same outage also a power upgrade is decided. The output power is expected to increase by approximately 50 MWe through increased efficiency and to result in an increase in thermal power from 1800 MWt to 2300 MWt (28%) and in electrical power from 620 MWe to 840 MWe (25%). In addition to several plant modifications, the control room is re-built to a new modern screen-based control room located in the same space as the old one, and with the same number of operators.

The human factors V&V employed the benchmark referenced approach. The ISV has to ensure that the control room modification and modernization are as least as good as the old one.

Theoretical underpinning

- OKG required to the contractor that the HFE activities follow NUREG-0711.
- The application of HFE analysis, design, and verification and validation activities was considered an integral part of the overall design process. A top-down, human-centered approach (as issued in IEEE Std 1023, IEC 964 or NUREG-0711) is being applied to the HFE activities.

Issues of integrated system validation

HFE V&V. HFE approach. HFE methods. Benchmark validations. Participants. Baseline considerations.

Validation stages

- Definition of ISV. Consider the concept provided in NUREG-0711.
- Pre-studies. After investigations and pre-studies (Project KRUM), including introduction of a structured approach to HFE, OKG chose a stepwise approach to modernizing the plant and to gradually introducing modern technology in the MCR.
- Overall evaluation process. The ISV was performed according to the modernization step, with the focus on one major plant area/work place (turbine or reactor) in each step.
 - The first baseline data was collected in the simulator located in Studsvik in 2005. In 2006 the simulator was moved from Studsvik to a new building on site.
 - The transformer was exchange during the outage in 2005, and in 2006 a new generator was installed as well as new software based operator interface and control systems. In 2007 the turbine operator work place was rebuilt to software, screen-based operator interface with large screen displays for plant overview (referred as TURBIC project).

OKG was responsible for HFE activities. In 2007, the human factors validation of the turbine I&C project was carried out, and in 2008 complementary human factors validation were performed. A new LP turbine was installed in 2009.

- The conceptual design for PLEX was completed by COP in early 2008, with most of the conceptual design approved by OKG for implementation into the basic design. The basic design was scheduled for completion early in the second quarter of 2009. Detailed design was completed in the end of first quarter of 2011 when the construction was started.
- A new base line was collected in 2010.
- A new ISV was planned for 2011.
- In 2011 a new deep cooling water intake was installed. The final implementation is planned for 2013 including the control room, new safety I&C and none safety I&C. It is planned the increase safety and power up rate (35% electrical and 28% thermal), new HP turbine, new emergency power supply with the installation of four new diesel generators, new RHR, new reactor protection system (RPS), two new seismically qualified electrical and I&C buildings, with safety related switchgear and controllers, the addition of a new Emergency Control Room (ECR) –the new ECR is housed in one of the new electrical buildings–, new process computer as well as new control rod maneuvering. All of this requires an almost complete redesign of the MCR and replacement of almost all of the primary plant operator interfaces.

Methods and measures

Because of new safety requirements, information and control equipment (including new safety systems) were stepwise installed into an adjacent control room, since the control room was quite compact and limited in space. The safety systems were functioning well separately as such, but in some cases their interfaces were inconsistent, leading to increased mental work of the operators, and the operators also had to move back and forth between the main and adjacent control room in order to obtain the necessary information to perform their tasks, often in dynamic and stressful situations where the information could change fast. In addition, the need to change obsolete equipment, reduction of maintenance costs, satisfying extended operation and safety requirements, and to improve competitiveness, led to modernization of the control room. After the modernization, the normal operation and control will be screen-based. The safety I&C system is digital. Safety related, conventional, mosaic-based operator interfaces located on a hard-wired safety panel and safety desk in the MCR are available –virtual duplicates are provided in the ECR. Under normal operating conditions, safety related plant equipment will be operated from the non-safety screen-based operator interfaces. Under conditions where the non-safety I&C screen-based operator interface system is degraded (or completely failed), shutdown and cool down are performed from the safety grade conventional panels and desks. Accidents will be managed using a combination of safety related and non-safety related interfaces.

The preferred operating interface is the screen-based operator workstations.

- In the modernization of the turbine in 2007, OKG was responsible for designing MCR, displays, education, HFE V&V and operator procedures. For the modernization of the reactor side of the MCR and other related operator interfaces, OKG assigned all of the HSI design and HFE requirements and responsibilities to the contractor based on the application of lessons learned from earlier experiences (OKG1 modernization and project TURBIC). The contractor had to:
 - Fulfill all HFE requirements.
 - Follow NUREG-0711.
 - Perform all HFE analyses.
 - Use OKG personnel and operators in the design work.

- Design a new emergency control room.
- Define the new concept of operations.
- Use human factors expertise.
- Update all procedures.
- Educate the staff (engineers, operators, and maintainers), with the exception of performing actual simulator training for operators.
- Perform all human factors verification and validation, including ISV.
- HFE organization. The control room HSI design and HFE work at OKG2 was the responsibility of COP, and closely supported by OKG through the use of “Sources of Knowledge” (SoK) –comprised of experienced current and ex-operators who have also been involved in other modernization projects at both OKG1 and OKG2–. The SoK and plant maintenance personnel were involved –with work performed both at the OKG site and in COP offices in Germany– in the application of HFE for changes to maintenance tasks and associated interfaces, including local panels and engineering workstations.
- HFE activities. At the stage of nearing completion of the basic design, there has been an important comprehensive effort to establish, perform, and document those HFE necessary to ensure the suitability of the basic design from a user-centered perspective. The HFE activities included: task analysis, HFE design verification, verification that the outputs from operating experience review were included, verification that the results of function analysis and allocation were included, and making a static paper-based task support verification using revised and new tasks and mark ups of the existing operating procedures.
The HFE activities ensure that the changes to the plant and the modernization of I&C and interface technology do not negatively impact human performance, increase errors, and reduce human reliability.
The application of HFE in control room and operator interface design using a process modeled on NUREG-0711 is a complex challenge. The guidance provided in various industry and regulatory documents is extremely helpful, but it cannot completely prepare the designer and engineers for the reality of a comprehensive nuclear power plant modernization project. New tools had to be created and implemented in the project and company structures; it was necessary to train and educate project personnel in the basic principles of HFE; the new tools and the project HFE program required the establishment of an interdisciplinary collaboration within COP, and between COP and OKG.
- Methods. Many of the detailed implementation procedures and methods for integrating the HFE activities into the project design process needed to be created, such as the development of tools to support the analyses, to structure the input and output data of HFE activities, and the processes for obtaining the resources necessary for implementation. A complete HFE design and analysis process was required, including the implementation plans for HFE activities for each of the project design phases, the handling of HFE issues, defining the nature, structure and level of detail for the documentation, the training material and the education of project personnel, and integration of personnel, work activities, and schedules. Some of the processes were:
 - Establishing interdisciplinary review requirements for HFE expert review of design documentation from other disciplines and review of HFE documentation by other disciplines.
 - Establishing processes to ensure changes to design inputs and outputs from HFE and HSI design activities to other disciplines (I&C system design) and vice versa.
 - Integration of HFE into the development of operating procedures. Operating procedures (at least, in draft form) are necessary to perform a static paper-based TSV to support verification of the basic design.
 - Integration and coordination of education and training activities, especially the

performance of job and task analysis with HFE.

- Basic and continuing education of project personnel in the requirements and interdisciplinary responsibilities for HFE.
- Integration of HFE activities into the project level 3 schedules and workflow projections.
- Promoting the understanding that the HFE activities are iterated throughout the design process.
- Coordination of work being performed in several locations in Germany and at the site in Sweden.

Additional tools to control and direct the required HFE activities in the ongoing design process were established. Procedures for governing the HFE Issues Tracking System, a task-oriented operating experience review, and the HFE activities required ensuring the adequacy of the basic design of systems and interfaces have been developed. Methods were developed for back-fitting documentation to take credit for work performed by the system engineers (especially function analysis and the definition of functional requirements, including the allocation of functions), documenting the task support verification activities performed by plant operators when they review panel design, display design, and system design during normal design processes, and to document the involvement and input of HFE experts in the design process (included in system clarification meetings, design review meetings, and other design workshops). These activities have needed to be documented and evaluated to determine what, if any, additional activities were needed. Checklists were developed by the HFE expert and included in the various engineering discipline design processes to ensure that usability, maintainability, and testability of equipment is being incorporated into the design of systems and components.

It also was necessary to tailor the HFE activities to ensure that the level of detail and the formality of the documentation were appropriate to the subject system or design, depending on complexity, extent of the changes, and criticality of the subject system or equipment for nuclear safety.

- Test-bed. A 3D computer-based tool was used for evaluating design alternatives and performing early HFE V&V. A detailed verification will be done in plywood mock-ups. When more detailed design phases and more dynamic tools are available, additional performance-based design evaluations and HFE V&V will be performed. Simulators are used for the ISV, the simulators of OKG2 CR, first located in Studsvik and later in Oskarshamn, served for the two baseline data.
- Reference of evaluation. The acceptance criterion was that the new control room should be at least as good as the old control room.

Main results and conclusions

- Lessons learned from the turbine-generator projects:
 - It was hard for the contractor to understand the existing functionality in detail, requiring a lot of tests in the simulator to achieve an acceptable functionality.
 - It was difficult to configure the installed software based operator interface to establish an acceptable operating environment. A new version of the software based operator interface would be installed during reactor upgrades.
 - HFE V&V confirmed the operators' opinion that additional improvements were needed in HSI functionality.
 - Improvements of functionality in operator interface were required from the authority, the operators and OKG before upgrade of the reactor workplace, especially in the alarm system (alarm handling, alarm pattern recognition and I&C alarm handling) as well as better screen-based displays.
 - OKG resources were severely stretched since they were responsible for most of the

| |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p>adaption to existing plant, all of the plant documentation, all HFE activities including basic design of operator interface, education and Human Factors V&V (HF V&V).</p> <ul style="list-style-type: none"> • Some issues related to the baseline approach to ISV. <ul style="list-style-type: none"> – Using results of ISV from a previous modification to establish a baseline: <ul style="list-style-type: none"> a. Is it still relevant? Are the earlier ISV results still valid? Does it represent the right scenarios? b. What is the effect if the crew has changed? c. What is the effect if the evaluators have changed? d. Would it be possible to use selected scenarios? e. What are the effects of changes made since the previous validation? f. What are the effects of improvements made in the design based on lessons learned from the previous mods? – Some pros and cons related to creating a completely new baseline are: <ul style="list-style-type: none"> a. Pros: (1) simple and classic; (2) does not require solving many issues; and (3) specific to the subject modification. b. Cons: (1) costly: need to develop all new scenarios and need to test 8 crews; (2) time consuming: longer preparation, 8 weeks of testing, and longer compiling results; and (3) hard to keep operator attention at a high level. • General lessons learned of the PLEX project: HFE was integrated in the PLEX project design process in accordance with NUREG-0711. Additional lessons learned will be applied to future projects for AREVA NP and for OKG. For example: <ul style="list-style-type: none"> – Increased integration of HFE into the corporate design processes as a separate and distinct engineering discipline similar to the classic engineering disciplines. – Integration of the HFE and the unique needs of HFE into the overall quality assurance programs, including definitions and requirements for independence in HFE V&V activities given the scarcity of qualified HFE experts. – Further establishing of tools (procedures, methodologies, software and equipment) and standards, minimum requirements, templates, and checklists in a general program for HFE in modernization and new plant projects. – Establishing required training programs for system engineers and management and giving them material and definitions to understand human factors. – Establish an education program for HFE to establish more certified HFE engineers. – Recruiting and training new staff for qualified HFE personnel. – Both OKG and AREVA NP are expanding their HFE capabilities and enhancing their processes and procedures to further ensure that HFE is an integral part of future projects. |
| <p>Recommendations</p> <ul style="list-style-type: none"> • The establishing of a baseline for ISV is recommended: before any changes that need validation; on the full scope simulator; using trained and licensed operators; using validated procedures; with scenarios that represent risk significant and complex tasks, associated with the modified aspects of the plant; and to be evaluated based on specified performance criteria based on operating experience review and identified weaknesses. • Additional recommendations were also included in the lessons learned of the results and conclusion characteristic. |
| <p>Further research</p> <ul style="list-style-type: none"> • On-going project. |
| <p>References</p> <ul style="list-style-type: none"> – Gunnarsson, T. (2007). Experiences from integrated system validation in OKG. In Braarud, |

P. Ø., Nystad, E., Strand, S., Skråning, G., Bye, A., Hildebrandt, M., and Massaiu, S. (2010). *The Halden Reactor Project Meeting on Integrated System Validation (ISV) – Status of Current Approaches to ISV and R&D Needs* (HWR-939). Halden, Norway: OECD Halden Reactor Project.

- Gunnarsson, T. (2007). Modernizing of Oskarshamn NPP with focus on control room issues. In *Proceedings of IAEA Technical Meeting on Integrating Analog and Digital Instrumentation and Control Systems in Hybrid Main Control Rooms at Nuclear Power Plants*, October 29 – November 2, 2007, Toronto, Ontario, Canada.
- Gunnarsson, T., Eliasson, M. (2010). The control room upgrade in Oskarshamn 2 modernization project, lesson learned from on going human factor design process. In *Proceedings of the Seventh International Topical Meeting on Nuclear Plant Instrumentation, Control and Human Machine Interface Technologies* (NPIC&HMIT), November 7-11, 2010, Las Vegas, Nevada, USA, pp. 1812-1821.
- Gunnarsson, T., Eliasson, M. (2011). The control room upgrade in Oskarshamn 2 modernization project lesson learned from ongoing human factor design. In *Proceedings of the Man-Technology-Organisation of the Enlarged Halden Programme Group Meeting* (EHPG), October 2-7, 2011, Sandefjord, Norway.
- Hill, D. (2010). Halden ISV workshop. Baseline for plant modernization. In Braarud, P. Ø., Nystad, E., Strand, S., Skråning, G., Bye, A., Hildebrandt, M., and Massaiu, S. (2010). *The Halden Reactor Project Meeting on Integrated System Validation (ISV) – Status of Current Approaches to ISV and R&D Needs* (HWR-939). Halden, Norway: OECD Halden Reactor Project.
- Hill, D., Krause, W., Gunnarsson, T. (2009). The application of a human factors engineering program for major modernization project in Sweden; tools, challenges, and lessons learned from practical experiences. In *Proceedings of the Sixth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies* (NPIC&HMIT), April 5-9, 2009, Knoxville, Tennessee, USA, pp. 2440-2450.

7.8.CASE STUDY 8: TIGER PROCEDURE FOR CONTROL ROOMS OF FORSMARK NPP – SWEDEN

| |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Study reference |
| Forsmarks Kraftgrupp AB NPPs. TIGER ¹⁵ procedure (“methods for specifying and reviewing new ergonomic designs”) in Forsmarks NPPs. |
| Domain of origin |
| Nuclear power plant. |
| Type of study |
| Natural working environment and/or simulation. The work within the procedure is carried out by a group of employees from different sectors of the NPP (end users, engineers and human factor experts) that are given certain roles and responsibilities within the group. The modernization of Forsmark NPPs is stepwise. The successive I&C modernization approach, over several outages, was chosen for several reasons, such as reducing the financial risks, being |

¹⁵ In Swedish, the acronym TIGER is for “Tillvägagångssätt vid specificering och Granskning av ny ERgonomidesign”.

easier to manage, and the lessons learned could help in the integrated installation of equipment in later stages in the modernization process.

Purpose of the study

The Forsmark BWR NPPs, three units supplied by Westinghouse Electric Sweden (at that time ASEA Atom), started operation between 1980 and 1985. In 1995, Forsmark Units 1 and 2 realized that the analogue I&C equipment needed replacement before 2005. The major factors contributing to the NPP I&C replacement were related with aging and obsolescence of equipment, technological obsolescence and a decrease in available expertise in analog equipment.

Forsmark NPPs use the five step procedure TIGER to incorporate Human Factors (HF) into the design process. TIGER is a procedure for specifying, developing and reviewing new and changed HMI in the plant, and runs in parallel with the normal project procedure at the plant. Forsmark NPP uses the procedure TIGER to ensure that modernizations affecting the operators HMI are designed and validated to meet requirements from both end users as well as design principals and standards used in the plant.

The TIGER procedure has been used under different forms in Forsmark since 1993. In 2002 the TIGER procedure was formed at its current name and form, and is since then used in all plants at Forsmark. The TIGER procedure has been employed in over 50 modernization projects.

Theoretical underpinning

- Norms and guides used are NUREG-0700, NUREG-0711, IEC 60964 and ISO 11064-1-3.

Issues of integrated system validation

Human factors V&V of HSI modifications. Method. Procedure. Evaluation team.

Validation stages

- Definition of verification and validation.
 - Verification: the equipment meets the specified requirements and composition. The verification should demonstrate that the operator tasks can be carried out in the expected way and that the intended functionality for the modification is achieved.
 - Validation: the system functions in its real environment. The validation should clarify that the modification interacts satisfactory with other systems and functions.
- Pre-studies. Control room philosophy and design study, and conceptual studies for replacement of analogue to digital I&C were ordered from different suppliers. The following requirements and goals were established:
 - The number of different HMIs should be kept as low as possible.
 - The operator's request was one single HMI concept in the main control room.
 - Create one platform for all future information and control systems, for both non-safety and safety systems.
 - The whole platform should be built for not failing to perform its functions due to any single failure.
 - Replace all old analogue I&C equipment on the reactor side where it is deemed cost beneficial.
 - Replace and integrate the control rod maneuvering system into the platform.
 - The process computer should be an integrated part of the new information and control platform, and the same HMI should be used for both control and process computers.
 - The long term goal for the turbine modernization was to replace all old analogue I&C equipment. The turbine protection should be upgraded from two to three channel turbine protection.
 - All changes, upgrades and modifications shall be made within the fixed outage period.

- Create a good maintenance situation.
- Overall evaluation process.
 - TIGER procedure is used by Forsmarks Kraftgrupp AB when modifications are made that influence the HSIs. The procedure is described in an instruction, which is a handbook, which defines methods that should be used in plant modifications and influence the working environment of operators in the main or local control rooms. The instruction gives practical advice and support for the analyses and is a basis for the design of operator interfaces.
 - The TIGER instruction is divided into the following eight main chapters:
 - 1) Procedure for the reviews and development of new ergonomic designs: goal of the procedure, quality assurance and acceptance, division of roles and responsibility, outline of the process, work model, resources and way of working, results, and time schedule and use of time. The ten “golden” principles described are: look at the control room to its entirety, follow a control room philosophy, think first in functions and only after that in concrete solutions, use a task analysis, use ergonomic knowledge, figure out how others have solved similar problems, involve operators in the modification work, do qualitative risk analyses, be consistent, and pursue simplicity, structure and a logical design.
 - 2) Initiation of TIGER and definition of scope: how the scope of the work should be established, how the modification should be described, how the modification should be evaluated, and how the process should be planned including timetable and resources.
 - 3) Identification and selection of tasks: support the identification of tasks that are influenced by the modification and select those which should be analyzed more in detail in later stages of the process.
 - 4) Description of the present situation: support the creation of written descriptions for how the selected tasks are performed today. The descriptions will consist of a task analysis and an error analysis, and if necessary contain a link analysis. The goal is to create measurable criteria to be used in the modification V&V.
 - 5) Checklists for the HSI design: the checklists give guidance for the design of operator workstations, computer displays and overview panels.
 - 6) Verification and evaluation of the suggested HSI design: guidance for how to verify and evaluate a concrete design suggestion. It goes through the scope, time schedule, goal, methods, criteria, analysis, evaluation, handling of deviations, and reporting. Guidance for the evaluation of new operator tasks and an interview guide with a set of proposed questions to be asked is provided.
 - 7) Validation of the plant modification: guidance for the validation of the plant modification in which a more general evaluation is done to ensure that the overall requirements on the main control room, local control rooms, operator stations, work environment, staffing, division of tasks, etc. are fulfilled. The aim is to ensure that old and new equipment are functioning efficiently tied together. Guidance on methods to be used, how the results should be analyzed and evaluated, and how possible deviations should be handled are given.
 - 8) References: list of the references used in the development of the instruction.
 - A decision must be taken whether a TIGER should be initiated or not. The assessment for initiating TIGER is made in consultation with the HSI group –a HSI group exists at each of the units, and is a standing group that handles HSI matters. Some of the criteria for the non-initiation of TIGER procedure relates with the fact that plant modification implies changes in existing HMI, that are done according to existing principles, or requires only small or no changes in the amount of information, the presentation of

information, the degree of automation and the operator tasks or working practices.

- The TIGER procedure is divided into five steps that run in parallel with the plants' modernization procedures. The steps comprise a description of the scope of the modification, a description of the present situation, HMI design review (suggestion for a new operator interface), verification and assessment of the suggestion, and validation of the plant modification.
- The steps in the procedure are documented in a report at the end of each step, providing a thorough documentation and traceability for the process of developing the HMI. A minimum of seven reports are produced: description of the scope, description of the present situation (including task analysis), proposal for the new operator interface, verification plan, verification results, validation plan, validation results, protocols with deviations from the verification and validation, and meeting records and minutes.

Methods and measures

Forsmark decided on an integrated system with a common safety and non-safety platform for the plant operator and applications. The integrated information and control system is highly standardized to reduce equipment and maintenance costs. During the I&C modernization processes, some of the implemented plant functions in Forsmark Units 1 and 2 have been: minor changes in the MCR to create space for screens and operator workplaces (1996); introduction of large screen presentation in MCR, computerized operating status check or computerized monitoring of safety functions (2000); introduction of principles for alarm handling and overview (2003); replacement of control boards and panels for non-safety electrical power systems (2005/2006); and operator workstations and large screen upgrade (2008).

- TIGER objectives. The objectives and purpose of the TIGER procedure are:
 - Provide support to the plant operation organization when designing new HMI.
 - Provide instructions and guidelines for how to specify, review, verify and validate new HMI.
 - Gather requirements and ideas regarding functionality and interface from end users.
 - Deliver basic data for HMI design through the current description and HMI specification including requirements for information and manual control.
 - Ensure that new and changed HMI meets requirements, standards and philosophy of Forsmark NPP.
 - Ensure that new and changed HMI are designed in an optimal manner with regards to operator viewpoint as well as safety and maintenance.
 - Ensure that the elements for specifying, reviewing, verifying and validating new HMI are carried out in accordance with project time plans and cost frames.
- TIGER conditions. Important conditions for a successful application of the TIGER instruction are that the TIGER process is initiated in good time, competent personnel are available for the modification project, and a good cooperation between the purchaser and the supplier of the modification project. The principles refers to the TIGER instruction as a tool to be used in the modification process; the purchaser is responsible for the execution of the TIGER activities; before a formal order can be made to the project it is required that the steps 1, 2 and 3 have been executed and that a report has been enclosed to the specification; all reporting initiated through TIGER is made to the purchaser.
- Steps in the TIGER procedure. The five steps in the TIGER procedure are as follows.
 - TIGER Step 1 – Scope description. The scope/extent of the procedure is decided based on the projects (plant modifications) influence on safety –which is derived from the systems' review group–, the projects influence on operator work and to some extent the projects influence on operational safety and personal safety. To decide the scope of the TIGER procedure, an analysis regarding problem objectives, function and relationships

is carried out with aid of checklists. A scope categorization matrix allows evaluating the influences on safety and on operator work. Dependent on scope, the TIGER procedure is divided into four categories, from A to D (category D requires the most work), to select the methods and scope for the V&V and also the current description.

The TIGER time schedule is outlined together with the nomination of personnel for the TIGER group. The development of instructions and training is also planned.

The scope description is concluded with a scope description report that documents, describes and motivates the decisions taken within the step.

- TIGER Step 2 – Current description (identification of tasks). Most of the work conducted in the control rooms is divided into work tasks where the operator uses written instructions to handle a given situation. All the work tasks (including existing and new tasks) that are being carried out in the existing HMI are identified. Then a selection of tasks is made for being assessed with respect to their influence on the new operator interface. These work tasks are analyzed separately by the use of a special template/questionnaire where the TIGER group has to answer a number of questions and also emphasize operational experience of the system. The current description shall show how these work tasks are performed and also define measurable criteria that later will be used for reviewing, verifying and validating the modification.

The results from these analyses are documented in the current description report that emphasizes strength and weaknesses of the existing HMI and also gives suggestions for improvements as well as emphasize operational experience of the existing HMI. The current description report is a basic data for the design department when designing the new or changed HMI, and the extent of this report is decided by the category from step 1. The report also contains the result from work task analysis.

- TIGER Step 3 – HMI design review. The main task is to define what kind of information and control the operator will need in order to carry out the task. In addition, suggestions are given for how the information should be displayed. The technical design department designs a new HMI considering the data given in the current description report. The basic data is then adjusted to harmonize with existing norms, standards and principles used for HMI design in the plant, and a concept design for new HMI is developed. Then the design is reviewed and eventually approved by the TIGER group, and especially the end users of the HMI and, in some cases, a human factors specialist.

To evaluate the proposed HSI, the same methods are used as for the description of the present situation and for the verification. To analyze and design a new HSI, a test environment –a full scope simulation, the main control room, or an operator station– is used. This evaluation may be carried out several times, especially in connection with large modifications.

- TIGER Step 4 – Verification. Verification is carried out once an approved HMI design has been finalized. The verification is divided into three different parts:
 - a. Verification of fulfilling specified requirements.
 - b. Verification of work tasks –comprising existing and new work tasks as well as work tasks that are not directly related to the project– from the current description report and the verification objectives.
 - c. Verification of HMI being in accordance with existing HMI design standards and principles.

The verification plan describes how, when and where the verification should be performed. The plan should contain the goals, conditions, methodology, realization, and data analysis. The instruction is used for the compilation of the plan. A subset of the work tasks (or scenarios) identified in step 2 is selected on the basis of tasks (or

scenarios) that are difficult to carry out, have a large safety influence or can have a large economic influence. The subset of tasks is later used to verify that these work tasks can be performed in the new HMI.

The TIGER group could be complemented with new members or be replaced entirely to achieve a more independent verification, i.e., if the design of the interface is done within the TIGER group, the verification should be carried out by other personnel or the verification group should be supplemented by some independent person who have not been involved in the design. Many times the group could be complemented with a human factors expert. Connected to the verification are also a number of interview questions regarding the HMI that the TIGER group shall answer.

Dependent on the category, the verification can be carried out in a simulator, a testing environment, operator's station or as an expert appraisal (judgment) in small and simple modifications that are assessed to have minor safety influence. The requirement on environment and scope is decided when the scope of TIGER is selected.

After completion of the verification, the results of all activities are documented in a verification report that is presented to the project orderer. The report lists observations that are categorized in three groups of measures: shall be taken, should be taken or can be taken.

The outcomes of the verification are analyzed before deciding whether to continue the project with the new HMI or if it has to be revised in any form.

- TIGER Step 5 – Validation. The validation is the final step in the TIGER procedure. The validation should demonstrate that the plant modification fulfils requirements on functions, performance and operator interfaces. The process to decide on if the physical and organizational design for operation is adapted to support a more efficient handling of functions for the control room personnel.

The validation plan states scope, objectives, hypotheses, method and analysis. A new subset of the work tasks, identified in step 2, is selected. The validation task subset is focused on work tasks and scenarios that are important for safety and should be representative for situations from normal operation to accident conditions.

Each work task is appraised by basis of a number of criteria and is documented in an appraisal protocol. Criteria for appraisal can be:

- a. Time to perform the work task.
- b. The tasks difficulty.
- c. The number of faults and mistakes made during the works task.
- d. The amount and content of communication with other parts if the shift team and the time this takes place within the work task.

The validation shall always be carried out by operators that have not been involved in the particular TIGER procedure earlier. Furthermore, the TIGER group can be complemented with various types of experts, such as human factors experts or system experts, to get an optimal evaluation of the plant modification.

Dependent on the category from step 1, the validation can be performed in either simulator or real environment. The validation can be carried out before or after the installation in the plant. A large modification, which implies a reconstruction of the simulator, should be validated before the operators' training is carried out in the simulator. Large and extensive modifications should be introduced in the full-scope simulator and should thus be validated in the simulator before the installation in the plant. If there are no possibilities for a validation beforehand and in the simulator environment, then a validation may be done in the control room when the installation has been carried out.

After completion of the validation, the HMI is evaluated from the basis of observations,

appraisal protocol, interviews, etc. The evaluation is then categorized according to three different assessment levels: approved, warning or not approved.

The results of the validation are documented in a validation report that contains the results for the assessment of hypothesis, observations made, appraisal protocol, interviews and questionnaires. The validation report also includes suggestions for further measures and improvements even if the validation has been approved.

- Human resources: roles within the process. The TIGER procedure is carried in parallel with the normal procedure for modernization, by a group of employees from different sectors of the plant that are appointed for a particular TIGER procedure, i.e., the composition of the group is determined on a case by case basis when the work is started and the scope of the work is determined.

To ensure that basic data and reports produced during the TIGER procedure are of high quality and are delivered in accordance with project time plans, different roles with clear responsibilities in the procedure were appointed.

- TIGER coordinator. Is nominated by the operating organization to be uniting the TIGER work towards the project orderer.
 - a. Establishes a TIGER group for each modernization project.
 - b. Coordinates the implementation of the various steps in the TIGER procedure towards the project orderer, project manager and design department.
 - c. Assure that the various steps in the TIGER procedure are implemented in accordance with the current description.
 - d. Informs all project coworkers of information relevant to the project.
 - e. Is the main contact for questions concerning HMI within the project and is also responsibly for the completion of the HMI specification.
 - f. Is responsible of V&V plans, i.e., coordinates validation of all modernization projects affecting the control room that are to be implemented during outage.
 - g. Documents the result from every step in the TIGER procedure.
 - h. Responsible for operator training and information related to the project.
- End users. Represent the personnel that will be working with the HMI once it has been put into operation. They could be control room operators as well as maintenance personnel. The end users are a very important part of the TIGER group as they hold information about how the system is used and presented in the current HMI.
- Design department engineers that work at the electrical design and engineering department. Responsible for the electrical design of the new I&C system and that the corresponding HMI is implemented in accordance with both the requirements from the current description document and the relevant norms, standards and principles used at the plant. Develops a new HMI concept to be reviewed by the TIGER group. Can also be a part of the V&V process as a system or platform specialist.
- Project orderer. The project orderer normally works within the plants operating organization. The project orderer is above all involved early in the procedure. The main responsibilities are:
 - a. Specifies each modernization project in a project specification document and is responsible that the specified requirements are fulfilled in that project.
 - b. Responsible for evaluating the modernization in accordance with the TIGER criteria.
 - c. Initiates a TIGER procedure for the assigned project if called for and assigns the task of performing a TIGER procedure to the TIGER coordinator.
 - d. Reviews and evaluates the results and reports/documents that are produced, i.e., current description document, HMI specification and V&V reports.

- Project manager. The project manager is responsible for the modernization project within which a TIGER procedure has been initiated and is, therefore, responsible for the implementation of the new or changed HMI in accordance with the project specification written by the project orderer.

As a summary of the TIGER group composition, the TIGER group works up to the verification step, and after that a change in the resources can be initiated, depending on who is responsible for the design of the operator interface. The validation should always be done by other operators than those who have been involved in the TIGER work. For the verification and validation it is possible to appoint additional resources depending on the scope of the plant modification.

- Time schedule. The time schedule for the TIGER work should be integrated with the plan for the plant modification project. Major plant modification should be started 2.5 to 3 years before the implementation. The task that determines the time schedule is the HSI design and the training of the operators which takes place about half a year before the implementation of the plant modification.

Main results and conclusions

- Results of TIGER. The results from the TIGER steps are documented in reports and on follow-up meetings, with all meetings being recorded and the minutes distributed to all persons concerned.
 - The pros with TIGER procedure are:
 - a. The end users of a system have the ability to influence the HMI design in a great manner.
 - b. Dividing the HMI design process –the end users defines the information– and manual control requirements, and the technical department implements these requirements in accordance with existing design principals.
 - c. The procedure generates an extensive and traceable documentation regarding the HMI. Makes it easier for the regulatory to review and evaluate the HMI of a modernization.
 - d. The cooperation between end users/operators and the technical department.
 - e. HMI is user friendly and elaborated.
 - f. Design flaws can be discovered early in the project.
 - The cons of TIGER procedure are:
 - a. Great costs when a lot of personnel is involved.
 - b. Time demanding as it means a lot of work.
 - c. Difficulty in meeting time plans when some personnel work in shift and others work office hours. This can lead to long time between meetings and slow up the process, thereby making it difficult to adapt to the project time plan.
 - d. Can some times be perceived as too much administration.
- Lessons learned and experiences made during the modernization of the NPPs.
 - Have different suppliers for doing a conceptual study over how the plant can be modernized with their equipment, covering the requirements and how the concept can be extended in the future.
 - A formal control room modernization procedure should be established, usually also required by the authorities, in order to secure the work environment of the operators in the modernized control room. In Forsmark NPPs, the procedure is TIGER.
 - Modernize complete sections of the control desk or complete operational tasks. Follow the existing operational instructions and cover all steps, preferably on one screen.
 - The modernization goals and the role of each group in the organization must be very clear. For each modernization project, personnel from the utility should be assigned full

time to the project, including primarily operations personnel and engineering staff (design and maintenance engineers).

- Existing organizational or administrative rules that should be considered, e.g., the focus on operations personnel. The operations personnel need to participate in the modernization tasks and the rest of the team should have confidence in the input provided by the operators. Use the benefits of integrated digital systems, giving operators more added values, e.g., task-oriented displays, information from other process systems that may be affected by the operational task, information from surveillance testing, information from peripheral systems.
- Integrate new documents into the existing plant documentation structure.
- Use the old existing graphical HSI as a basis for the requirements concerning tools and base display elements in the new HSI. Define basic display elements needed to create the desired displays and define the preferred dialogues. The design of displays for a system is an iteration process between the supplier and the customer. A good result requires good specifications.
- Ensure that the existing naming convention is applied in the new system. One person or a group of persons should assign names for new signals and objects.
- Changing from analogue to digital I&C will imply that maintenance personnel will take over work that previously was done by computer personnel. The necessary training of maintenance personnel should be considered. The maintenance personnel should be aware of that they are responsible for everything from process interface to operators HSI. Use simulator and simulator personnel to produce and validate user documentation and for operator training.
- I&C platform infrastructure shall support a controlled management of new software and hardware, configuration control and compliance. Strict control of upgrades should be applied. When upgrades are performed, the supplier should be responsible for upgrading the whole platform. Simulators for operator training and validation of HSI solutions shall be built up and be based on the I&C platform infrastructure.
- It is good practice to implement a testing and development system. The test system is a qualitative copy of the platform installed in the plant that can be used for verifying application software design changes and expansions on a regular basis.
- Direct participation in the project is one of the best forms of training and education for operations and maintenance personnel. During design of the new information and control system platform, Forsmark had three persons participating in the Westinghouse project during 2 years.
- Conclusions of the modernization processes of the NPPs. The Forsmark goals of the modernization have all been met:
 - An integrated platform has been achieved including one common operator interface for control and information systems.
 - The operating staff has participated in the HSI design and appreciates the end result, even though the initial difficulties with alarm philosophy after the first step of the modernization were challenging.
 - Extremely cost effective maintenance work has been achieved due to fewer types of equipment and lower failure rates as well as the achievement of a common software version throughout the platform.
 - All modernization steps have been performed within time limits of planned outage periods, and never caused any outage delays.

Recommendations

- Some recommendations on control room modernization refers to the covering of complete

sections of the control room or complete operational tasks, the establishment of clear goals and role of the plant personnel, as well as the direct involvement of plant personnel in the modernization process. Additional recommendations have been included as lessons learned in the characteristic of main results and conclusions.

- Recommendations on the TIGER procedure:
 - The TIGER procedure is a good tool for planning, specifying, designing, verifying and documenting the work and result related to an HMI modernization. However, it requires that the people working with TIGER have good knowledge regarding planning and implementing the work within the procedure. There are still areas of improvement and the procedure could be more effective with more personnel with key roles in TIGER being more familiar with the procedure.
 - As the TIGER procedure runs in parallel with the normal project procedure at Forsmark, it is important to have a good planning so that both procedures (TIGER and modernization) are synchronized with each other.

Further research

- The modernization program in Forsmark will continue for many years. Extensive modernization activities for power upgrade and plant operation beyond the designed life time of 40 years are in progress. Forsmark has performed a pre-study regarding necessary upgrade and replacement activities based on the future need for extensions and functional improvements as well as the suppliers' product lifecycle management program. The pre-study indicated that the platform for HMI in the MCR of Forsmark Units 1 and 2, the operator workplaces, had to be replaced and it is planned to be in operation by the year 2014. In order to sustain a safe and reliable operation of the platform to the year 2030 and beyond, a renewed long term agreement with the original supplier Westinghouse and the ABB's Automation Sentinel software management program has been signed.
- The TIGER procedure is being used in the HMI modernization process of the Forsmark NPPs Units 1 and 2 in Sweden.

References

- Blomstrand, J.-Å. (2009). Forsmark 1&2 NPP – Step wise strategy for modernization of I&C systems. In *Proceedings of the Sixth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies* (NPICT&HMIT), April 5-9, 2009, Knoxville, Tennessee, USA, pp. 1425-1438.
- Kloow, L. and Rydahl, I. (2004). Appendix D. Experience from successive modernization of instrumentation and control systems of Forsmark 1&2. *Managing Modernization of Nuclear Power Plant Instrumentation and Control Systems* (IAEA-TECDOC-1389). Vienna, Austria: IAEA, pp. 95-103.
- NEA/CSNI/R(2005)10. *Safety of modifications at nuclear power plants. The role of minor modifications and human and organisational factors. Appendix 7. One example of instructions for incorporating human factors in a modification process*. Paris, France: Organisation for Economic Co-operation and Development (OECD), pp. 79-87.
- Ohlson, E. (2009). TIGER - A method for incorporating human factors into NPP modernizations. In *Proceedings of the Sixth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies* (NPICT&HMIT), April 5-9, 2009, Knoxville, Tennessee, USA, pp. 2430-2439.
- Westinghouse Electric Company (2002). *Modernization: Bringing a Plant Up-to-Date. Westinghouse World View*, 6-7.

7.9.CASE STUDY 9: HUMAN FACTORS V&V OF CONTROL ROOM OF LUNG MEN NPP – TAIWAN

| |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Study reference |
| National Tsing Hua University, General Electric and Atomic Energy Council of Taiwan. Human factors verification and validation of the Lungmen NPP in Taiwan. |
| Domain of origin |
| Nuclear power plant. |
| Type of study |
| Simulation. Performance based evaluation. The participants were from General Electric (GE), Taipower Co. (TPC) (operators and simulator test personnel), GE HFE subcontractors and end users (future candidate operators of the Lungmen control room). Phased approach, with three stages of the human factors verification and validation, starting in 1998 (1998-2000, 2000-2005, and from 2005). |
| Purpose of the study |
| The Lungmen Nuclear Power Plant (Lungmen NPP) Advanced Boiling Water Reactor (ABWR) is under construction in Taiwan, owned by TPC, and consists of two GE ABWR units, each with 1350 MW electrical output. The I&C systems of the Lungmen NPP are based on modernized fully integrated digital design, and the HSIs of Lungmen NPP are VDUs, soft control for operators to manipulate and to know the status of the equipment and plant information. The MCR HFE V&V is a commitment specified in the preliminary safety analysis report, chapter 18. |
| Theoretical underpinning |
| <ul style="list-style-type: none"> • The technical guides for the evaluation of the control room were NUREG-0700 and NUREG-0711. The model of NUREG-0711 was the review criterion for the digitized control room of the newly constructed nuclear power units of the Lungmen NPP. • The Human Factors Verification & Validation Implementation Plan (HF V&VIP) defined the methods and criteria for conducting the Human Factors V&V in accordance with accepted human factors practices and principles. |
| Issues of integrated system validation |
| HFE V&V phases. Simulations. Methods. Scenarios. Participants. |
| Validation stages |
| <ul style="list-style-type: none"> • Concept of V&V. V&V is one element of NUREG-0711, in the context of HFE assures that the design of the HSI conforms to HFE principles, and is correctly implemented in a final, “as built” form and free of safety issues and human performance issues. <ul style="list-style-type: none"> – Verification is the process of determining and documenting that an implemented design (such as a product, process, procedure, method) meets its specifications –if the design was implemented appropriately. – Validation is the process of determining and documenting that the design effectively serves the purpose for which it was intended –if the appropriate design was implemented. • Phases of V&V. The top-down HFE PRM, specified in NUREG-0711, was adopted to assist the evaluation of Lungmen NPP advanced control room design. The implementation of HFE V&V plan consisted of five process steps: (1) HSI Task Support Verification; (2) HFE design verification; (3) integrated system validation; (4) issue resolution verification; and (5) final plant HFE/HSI design verification. |

The V&V activities for the Lungmen project were separated into three phases: HF V&V-1 (process steps 1-4, 1998-2000), HF V&V-2 (process steps 1-4, 2000-2005), and HF V&V-3 (process steps 1-5, from 2005). The principal scope for each HFE phase is presented in the table 4.

Table 4. Scope of the HFE phases

| HFE phase | Principal Scope | NUREG-0711 V&V Process steps | | | |
|-----------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------|---------------|-----|--------------|
| | | 1 | 2 | 3 | 4 |
| | | TSV | Design Verif. | ISV | Final Verif. |
| 1 | Displays of 56 systems | 1 | 2 | 3 | |
| | MCR and RSD | 1 | 2 | | |
| 2 | Displays of 56 systems | 1 | 2 | 3 | |
| | MCR and RSD | 1 | 2 | 3 | |
| | SPDS | 1 | 2 | 3 | |
| | Alarm system (static priority) | 1 | 2 | 3 | |
| 3 | Using simulator: Full HSIs in MCR, procedures, training manuals, communication equipment, lighting, staffing and room occupancy, shift rotation | 1 | 2 | 3 | 5 |
| | At unit 1 facilities: Real unit 1 HSIs in MCR, MCRBP & RSD, procedures, communication equipment, lighting, staffing and room occupancy, tagout facility, habitability and floor design, interfaces with TSC and EOF | 1 | 2 | 3 | 5 |
| | Maintainability | 1 | 2 | 3 | 5 |

The HF V&V activities were separated for collecting early data before the final delivery of the design, and to address project dynamics of multiple design organizations. The phased approach met the requirements of the HFE PRM while providing the design team and regulatory reviewers with early data to confirm the design of the HSI. Items to be addressed later and that meet HFE issue criteria were tracked using the HFE Issue Tracking System (HFEITS). The three phases of the HF V&V were as follows.

- 1) The first phase was labeled as HF V&V-1. Seven hundred operator graphics displays for fifty-six systems of the Lungmen control room NPP were evaluated using the partial-scope Lungmen NPP simulator (General Electric Test System –GETS simulator). The displays were verified and partially validated for normal operating conditions, by a multi-disciplinary team.
- 2) The second phase consisted of HF V&V-2 and HF V&V-2.5.
 - HF V&V-2. Five principal HSIs –MCR panels, MCR operator graphics displays, Remote Shutdown Panels (RSD), MCR Alarm and Annunciator System (AAS), and the MCR Safety Parameter Display Subsystem (SPDS)– were verified for compliance with HFE requirements and validated against HFE acceptance criteria using the Lungmen simulators. The V&V of the five HSIs was performed at GE’s Nuclear facilities in San Jose, California during the Factory Acceptance Test (FAT) phases of the Lungmen NPP simulators (baseline and updated versions).
 - HF V&V-2.5. The main objective of HF V&V-2.5 was to further validate the HSIs and human performance for a representative sample of the expected Lungmen operators, by using Lungmen candidate operators as test subjects, for dynamic validation testing with the update simulator at the Lungmen site. V&V-2.5 was completed in June, 2006.

- 3) The third phase was named HF V&V-3. Evaluations in the final V&V phase must use representative tasks, actual system dynamics, and real operators. The fully integrated HSIs, including any changes to procedures and operator training, as well as other as-built MCR design (e.g., adequacy of the MCR lighting) will be verified and validated in this phase. The Lungmen Full Scope Simulator (FSS) will be used in HF V&V-3 as the platform. The HSI in Lungmen FSS shall have the full functionality similar to that found in the actual control room, i.e., simulate the nuclear steam supply system (NSSS) and the balance of plant (BOP) systems for the reference plant as well as include all of the major nuclear, conventional, service and safety systems.

Besides, the following activities were performed in 2007:

- Verification and validation of operational displays on Class 1E VDUs. Verification of the Class 1E displays was performed in April 2007, and limited validation of the displays was performed in August-September 2007, with TPC operator and HFE personnel participating in the GE HFE Team.
- Maintainability HFE Check for I&C Cabinets. The check will be performed at site for those unit cabinets not performed at vendors' factories.

Methods and measures

The main control room of Lungmen NPP consisted of the Wide Display Panel (WDP), the Main Control Console (MCC), and the Shift Supervisor Console (SSC):

- Large WDP is centrally located in the MCR and the information provided on the three vertical panels is visible to the crew members in the MCR. The WDP provides alarms, system information on a large overview dynamic mimic and a seventy-inch Large Variable Display (LVD).
- Operating crew monitor and control plant systems from the MCC using VDUs with touch-screen. The MCC has both safety and non-safety systems, with the divisionally separated safety systems located on the left side of the MCC.
- Shift supervisor monitor the control room activities from the SSC.

The major HSI for operation of the plant consisted of the VDU with a touch-screen feature. A total of forty-five VDUs were in the control room, forty-two of which have monitor and control functions (twelve VDUs are for safety systems while thirty VDUs are for non-safety systems) located on the WDP and MCC; the remaining three VDUs, with monitor function only, were located on the SSC. The alarms, displays and control switches in the MCR were classified, by importance, into two categories: fixed position design (the most important alarms, signal displays and control switches) and variable position design (the majority of components).

- Methods. The HFE PRM of NUREG-0711 assisted the evaluation of Lungmen NPP advanced control room design. Methods and criteria for conducting the HF V&V were defined in the HF V&VIP. A description of the methods and participants of each HF V&V phase is provided.
 - First phase: HF V&V-1. The method of validating the usability of a display was a dynamic walkthrough, based on a one system at a time display evaluation for normal operational sequences. The evaluation relied on the Lungmen system operating procedure and user expertise, as guides for task execution. The display user, preferably a Taiwan Power Company person with operation experience, followed the procedure and used the display to perform operator tasks and gradually conducted normal system evolutions. The display user and observers –HFE, trainers– recorded observations and relevant comments during the walkthrough.
 - Second phase: HF V&V-2. The participants were personnel from GE, TPC, and GE HFE subcontractors. The participants made up a V&V-2 team, a group of four TPC personnel that participated in predominantly subjective validation by responding to

questionnaires, and a group of four GE personnel that participated in objective validation by role playing the operating crew response to various simulated scenarios. Verification was conducted primarily in parallel with the testing and certification of the baseline and updated simulators.

Validation began with administering questionnaires to TPC simulator test personnel during simulator FAT in order to collect subjective data on HSI validity in five areas: usability, monitoring and detection, situation assessment and awareness, workload, and communication and teamwork. Validation continued with collection of objective data on HSI validity using operator crew role-playing in response to twenty-one simulated scenarios. Questionnaires were given to the four TPC simulator FAT members. The participants completed the questionnaires following their performance of role-playing using the scenarios.

- Second phase: HF V&V-2.5. The V&V-2.5 used six test subjects in two crews (three test subjects per crew). The test subjects were a shift MCR supervisor, a unit MCR reactor operator, and a unit MCR assistant reactor operator.

Nine simulated scenarios were conducted in V&V-2.5. Eight of the twenty-one scenarios used in HF V&V-2 were subsequently simulated in V&V-2.5. The scenarios were role-played twice, one at a time by the two crews. And for real operator performance and workload evaluation purposes, test subjects were precluded from knowing what scenario was about to be simulated. Criteria for selecting scenarios were:

- a. Scenarios of HF V&V-2 because V&V-2.5 test results could be compared to V&V-2 test results, and made an efficient use of the scripts developed during V&V-2.
- b. Scenarios addressing the testing recommendations from V&V-2.
- c. Scenarios from V&V-2 with high peaks of workload.

- Third phase: HF V&V-3. The performance of HF V&V-3 will be further defined in detailed procedures. The integrated design will be evaluated using the Lungmen FSS. On the other hand, in 2007 the verification and validation of operational displays on Class 1E VDUs was performed, with TPC operator and HFE personnel participating in the GE HFE Team, when the VDU FAT was ongoing.

- Simulators. The HF V&VIP used several test and evaluation environments, as the design proceeded: GETS, the baseline simulator, the updated simulator, FSS, the MCR and the RSD panels.

According to regulators, the Lungmen simulator shall be a true replica (high fidelity) of the Unit 1 MCR and DCIS (Distributed Control and Information System). The Lungmen simulator had dual functions in the Lungmen Project implementation phase: (1) the simulator development work lead the main control room development work, i.e., the simulator facilitated the main control room design and also the conduct of the MCR HFE V&V; (2) the simulator is suitable for operator training to meet the requirement before two years of initial fuel loading of Lungmen Unit 1. To assure the nuclear operation safety, the nuclear regulatory body ROC's Atomic Energy Council (ROCAEC), reactor operators licensing guidelines require that there are sufficient licensed senior reactor operators and licensed reactor operators to operate the plant. Therefore, Lungmen PSAR chapter 13.2 commits to select qualified operator candidates to attend the reactor operators training program and the candidates shall practice manipulating the controls of the plant on Lungmen FSS simulator.

The development of the Lungmen simulator started without a reference plant for the design of the Unit 1 DCIS, and more issues than expected came up during the simulator design. There were two Unit 1 DCIS design freeze dates. Corresponding to those dates, there were two data sets for the simulator design implementation, one based on October 1998 Unit 1 DCIS data, the other based on May 2003 data. Accordingly, the baseline version simulator

and the update version simulator were resulted. The simulator FAT was started on December 2002. Over 1000 discrepancy reports (DRs) were issued through testing activities. The DRs were categorized into four groups as indicated in the table 5. A root cause of many DRs was the interface problems due to the different versions of design inputs used by the various suppliers. An enhancement version of the configuration management plan for the Lungmen Simulator was requested to be able to ensure compliance with ANSI/ANS 3.5¹¹ for all hardware and software configuration changes, documentation control and test program from multiple vendors.

Table 5. Summary of simulator factory acceptance test

| Classification | Percentage (%) ^a |
|----------------------------------|-----------------------------|
| Simulator modeling development | 30 |
| Control room panels construction | 10 |
| MPL display development | 50 |
| PCS function development | 30 |

^a Some DRs cover more than one classification.

The update simulator was delivered to site in May 2005 (for operator training needs); due to schedule constraints, the update simulator had available only 57 of 94 systems graphic displays. Some functions that were not in the baseline and updated simulators included power generation control system, on-line procedures subsystem, and dynamic alarm prioritization. To totally resolve the simulator issues, a FSS implementation plan was carried out at site. The Lungmen FSS control room panels are total replicas of the Lungmen NPP MCR panels. The FSS for Lungmen ABWR completed its Site Acceptance Test (SAT) and Availability Test (AVT) in June 2008 and was ready for training and operator licensing as well as for HFE V&V-3 implementation.

- Participants. Personnel from GE, TPC, GE HFE subcontractors and end users.
- Scenarios. The scenarios represented a majority of the scenarios required by NUREG-0711 and ANSI/ANS 3.5¹¹ to be simulated, fully consistent with the HF V&V-2. The twenty-one scenarios simulated in HF V&V-2 were: (1) startup (control rod withdrawal for criticality – full manual); (2) startup (start motor driven reactor feedwater pump –MDRFP– and transfer feedwater from low flow control to master level control); (3) startup (transfer to run mode), (4) startup (turbine and generator startup); (5) startup (generator synchronization and initial loading); (6) plant shutdown from rated power (starting MDRFP, stopping turbine driven reactor feedwater pumps –TDRFP–, transfer feedwater from master level control to low flow control); (7) shutdown from outside of MCR; (8) LOCA inside and outside containment; (9) trip of all reactor internal pumps; (10) loss of condenser vacuum, including main steam isolation valve –MSIV; (11) loss of normal and emergency feedwater; (12) standby liquid control system –SLC– pump flow test; (13) high pressure core flood system –HPCF– flow rate test; (14) diesel generator to off site power load transfer test; (15) main turbine trip; (16) inadvertent stuck open safety relief valve; (17) loss of coolant accident with loss of off site power; (18) pressure regulator failure –open/closed; (19) anticipated transients without scram –ATWS– (control rod groups failure to scram and fails to initiate selected control rod run-in –SCRRI–); (20) emergency core cooling system inoperative; (21) reactor pressure vessel flooding. In the HF V&V-2.5, scenarios number 2, 7, 9, 11, 16, 17, 18, 19 were used, and also a scenario of loss of all non-safety controls, display and alarms.

Main results and conclusions

V&V-1 through V&V-2 were completed from where displays, control room panels and readouts had been HFE V&V by running the MCR through a comprehensive set of plant operating and transient scenarios on simulator.

- The main results of the HF V&V phases were:

- HF V&V-1. The initial verification confirmed that the inventory, and the control and information content of the displays, addressed the operator task requirements prescribed by the completed task analyses. The verification indicated that displays were generally implemented appropriately with respect to HFE-related specifications. More standardized design and layout of screen objects by display designers and software display builders improved the consistency of the look and feel of the displays. The validation partially confirmed that the display design for normal operation of individual systems was appropriate for the Lungmen MCR operator crews.
- HF V&V-2. The performance of HF V&V-2, based on the HF V&V-2 completed in 2005 using the FAT versions (baseline and update) of the Lungmen Simulator, concluded that additional HFE V&V was needed to fully validate the individual HSIs, the completely integrated HSI, and human performance. As Lungmen operators were not fully available for the conduct of HF V&V-2 operator role-playing activity, domestic HFE experts suggested to perform an extension validation activity: the HF V&V-2.5 phase.
- HF V&V-2.5. The preliminary findings included: (1) the shift supervisor relied primarily on the WDP and oral communication with operators, and much less on VDU displays at the SSC; (2) the large variable display was very effective for crew coordination. A training consideration might be to establish its use as a more standardized crew practice; (3) high workload was observed especially at the beginning of a scenario when each crew tried to examine and assess the situation. Workload decreased as each crew began recovery actions; and (4) cognitive workload probably increased whenever an operator experienced confusing, inconsistent, or missing information.
- HF V&V-3. In the verification and validation of the operational Class 1E displays in 2007, ninety-four findings (seventy-four on verification, and twenty on validation) were reported.
- The HF V&V is on going, as the MCR design needed to go through the HFE V&V-3.

Recommendations

- An important aspect of the Lungmen HFE program was the direct involvement of the end user, Taiwan Power Company, throughout design, development and implementation to ensure that the process for the design is compliant with the HFE principles, and that the necessary displays, control, and alarms were provided to support the personnel tasks.
- Late completion of the FSS had an impact on operator training and licensing examination and on the schedule for completion of the HFE V&V implementation. Three feedbacks were:
 - Without a reference plant to start with for the design of a simulator, a gap between the simulator design data set and the DCIS design in progress is inevitable.
 - Until sufficient high design completion of the reference plant is achieved, is advisable not to start the simulator design.
 - Two years requirements imposed very severe constraints on implementation.

Further research

- The HSIs for the Lungmen NPP as designed, verified and validated so far had proven essentially in compliance with relevant regulatory guidance. The MCR design still needed to go through the HFE V&V-3 which must use representative tasks, actual system dynamics, and real operators for final ISV and as-built design verification. The other as-built MCR design will also be verified and validated.

References

- Chuang, C.-F., Chou, H.-P. (2008). Design, development and implementation of the human-system interface for Lungmen nuclear project. *IEEE Transactions on Nuclear Science*, 55(5), 2654-2661.
- Chuang, C.-F., Chou, H.-P., Chen, Y.B., Shiao, H. (2008). Regulatory overview of digital I&C system in Taiwan Lungmen project. *Annals of Nuclear Energy*, 35, 877–889.

Additional references:

- Chuang, C.-F., Chou, H.-P. (2005). Investigation of potential operation issues of human-system interface in Lungmen nuclear power project. *IEEE Transactions on Nuclear Science*, 52(4), 1004-1008.
- Hwang, S.-L., Liang, S.-F. M., Liu, T.-Y. Y., Yang, Y.-J., Chen, P.-Y., Chuang, C.-F. (2009). Evaluation of human factors in interface design in main control rooms. *Nuclear Engineering and Design*, 239, 3069–3075.
- Lee, C.-M., Tsai, W.-C., Wong, K. W. and Pang, T. (2009). The new generation nuclear power plant simulator – The Lungmen ABWR simulator. In *Proceedings of the Sixth American Nuclear Society International Topical Meeting on Nuclear Plant, Instrumentation, Control and Human-Machine Interface Technologies (NPICT&HMIT)*, April 5-9, 2009, Knoxville, Tennessee, USA, pp. 2202-2213.
- Lin, C. J., Jou, Y.-T., Yenn, T.-C., Hsieh, T.-L. and Yang, C.-W. (2009). A study of control room staffing and workload from the human information processing perspective. In *Proceedings of the 2009 IEEE International Conference on Networking, Sensing and Control*, March 26-29, 2009, Okayama, Japan, pp. 303-307.

8.SUMMARY

The literature review or state of the art report has focused on performance-based evaluations (integrated system validation) of practical applications (case studies) in upgraded and computer-based control rooms in the nuclear domain.

A total of nine methodological case studies of human factors evaluation (verification and validation) of NPP control rooms, with special focus on integrated system validation projects, were reviewed: the CASU method (Finland) applied in Olkiluoto NPP, and especially in Loviisa NPP; EPR Flamanville Unit 3 NPP (France); APR1400 NPP (South Korea); HFE V&V applied in José Cabrera, Almaraz and Vandellós NPPs (Spain); Ringhals Unit 2 NPP –TWICE project– (Sweden); Oskarshamn Unit 1 NPP (Sweden); Oskarshamn Unit 2 NPP –PLEX project– (Sweden); TIGER procedure applied in Forsmark NPPs (Sweden); and Lungmen NPP (Taiwan). Some of them are currently on going projects.

The domain of origin was nuclear power plants in all cases studies, although the CASU method has also been used in empirical studies in other domains.

The large and extensive plant design modifications, ISV activities, are carried out in a simulator environment (full scope simulators). Normal work situation (real environment) is also mentioned in some studies. The participants in the validation processes were representative end users of the HSIs, operating crews, with future candidate operators of the plant control room in the new designs. When the end users were not available, the test subjects were plant personnel, such as designers or simulator test representative (instructors).

A one step upgrading process of the control room was carried out in two NPPs, Ringhals Unit 2 and Oskarshamn Unit 1. However, a longitudinal or stepwise approach was followed in the

applications of the CASU method, EPR Flamanville Unit 3, Oskarshamn Unit 2, Forsmarks or Lungmen NPPs.

The HFE V&V plant modifications processes for NPPs control rooms are under regulatory requirements. The technical guides for the evaluation of the control room were based on norms, standards, and guidelines, such as NUREG-0711, NUREG-0700, ISO 9241, ISO 11604, IEEE Std 1023, IEC 964 (60964), NUREG/CR-6393, EPRI (2004) and EPRI (2005). The design review process in all upgrade and modernization case studies referred to NUREG-0711 model.

Measures of performance of the plant and personnel are addressed in the industrial case studies. Plant performance measures relate with deviations from predefined ideal process values. The crew task performance may include a combination of primary task measures –as monitoring and detection, situation assessment, response planning, and response implementation– and secondary tasks and usability measures of the HSI. The cognitive factors cover situation awareness and workload. Also, work practices, teamwork and communication are referred, as well as, in some cases, anthropometric/physiological factors.

A repertory of methods for data collection is usually described in the case studies, measuring different aspects of human performance. The methods are applied in different stages of the data collection –before, during and at the end of the test sessions. Observations, individual and group interviews, focus groups, task analyses, (cognitive) walkthroughs or talkthroughs, expert evaluations, questionnaires, video and audio recording, online rating, and usability tests or questionnaires of the HSI are some of the presented methods and techniques.

Current approaches or industrial projects on ISV processes are placed together in this document. There is not an attempt to summarize all the results or lessons learned, but we intended to present them in a very detailed and thorough way for each study in the previous tables. Most of the reviewed studies included recommendations as well as research and development needs on ISV.

As the nuclear industry is currently at a stage where many upgrade projects (control room modernizations) are being performed, and new NPPs are planned to be build, the methodological approach and practical experience described in this report may be used as input for other ISV projects.

The state of the art report may be useful for researchers, developers, utilities, vendors, or designers of high reliability industries who are planning to go through modernization processes or developing new control rooms, and have to test or evaluate them from the human factors perspective.

9. REFERENCES

- Blomstrand, J.-Å. (2009). Forsmark 1&2 NPP – Step wise strategy for modernization of I&C systems. In *Proceedings of the Sixth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies* (NPIC&HMIT), April 5-9, 2009, Knoxville, Tennessee, USA, pp. 1425-1438.
- Braarud, P. Ø. and Skraaning, G. (2006). Insights from a benchmark integrated system validation of a modernized NPP control room: performance measurement and the

- comparison to the benchmark system. In *Proceedings of Fifth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Controls and Human-Machine Interface Technologies* (NPIC&HMIT), November 12-16, 2006, Albuquerque, New Mexico, USA.
- Braarud, P. Ø. and Strand, S. (2011). *Human factors integrated system validation - lessons learned from NPP modernisation projects* (HWR-986). Halden, Norway: OECD Halden Reactor Project.
 - Braarud, P. Ø., Nystad, E., Strand, S., Skråning, G., Bye, A., Hildebrandt, M., and Massaiu, S. (2010). *The Halden Reactor Project meeting on integrated system validation (ISV) – Status of current approaches to ISV and R&D needs* (HWR-939). Halden, Norway: OECD Halden Reactor Project.
 - Braarud, P. Ø., Skraaning G., Broberg, H. (2005). Integrated system validation: plans and status of the first calibration experiment. In *Proceedings of the Man-Technology-Organisation of the Enlarged Halden Programme Group Meeting* (EHPG), October 17-21, 2005, Lillehammer, Norway.
 - Braarud, P. Ø., Skraaning, G. and Nihlwing, C. (2007). Integrated system validation experiences from a benchmark ISV and HAMMLAB workshop on work method assessment. In *Proceedings of the Man-Technology-Organisation of the Enlarged Halden Programme Group Meeting* (EHPG), March 12-16, 2007, Storefjell, Norway.
 - Braarud, P. Ø., Strand, S., Svengren, H. (2010). 1st ISV experiment on criterion-based human performance measures. In *Proceedings of the Man-Technology-Organisation of the Enlarged Halden Programme Group Meeting* (EHPG) (HPR-372), March 14-19, 2010, Storefjell, Norway.
 - Braarud, P. Ø., Strand, S., Svengren, H., Skråning, G. and Nystad, E. (2009). *Halden White Paper “1st ISV experiment on criterion-based human performance measures”* (HWhP-032, Issue 1, 2009-09). Halden, Norway: OECD Halden Reactor Project.
 - Braarud, P.Ø., Andresen, G. (2005). *The a-b-c benchmark validation of the upgraded Oskarshamn 1 control room*. IFE/HR/F-2005/1275. Halden, Norway: Institute for Energy Technology. *Confidential*.
 - P. Ø. Braarud (personal communication, September 14, 2012).
 - Chuang, C.-F., Chou, H.-P. (2005). Investigation of potential operation issues of human-system interface in Lungmen nuclear power project. *IEEE Transactions on Nuclear Science*, 52(4), 1004-1008.
 - Chuang, C.-F., Chou, H.-P. (2008). Design, development and implementation of the human-system interface for Lungmen nuclear project. *IEEE Transactions on Nuclear Science*, 55(5), 2654-2661.
 - Chuang, C.-F., Chou, H.-P., Chen, Y.B., Shiao, H. (2008). Regulatory overview of digital I&C system in Taiwan Lungmen project. *Annals of Nuclear Energy*, 35, 877–889.
 - Collier, S. and Green, M. (1999). *Verification and validation of human factors issues in control rooms* (HWR-598). Halden, Norway: OECD Halden Reactor Project.
 - CSN (2009). Instrucción de seguridad IS-21 del CSN sobre requisitos aplicables a las modificaciones en las centrales nucleares. (Nuclear Safety Council Instruction number IS-21, of January 28th 2009, on the requirements applicable to modifications at nuclear power plants. Published in the Official State Gazette (BOE) number 43 of February 19th 2009).
 - CSN (2010a). Instrucción de seguridad IS-26 del CSN sobre requisitos básicos de seguridad nuclear aplicables a las instalaciones nucleares. (The Nuclear Safety Council’s Instruction IS-26, of 16th June 2010, on basic nuclear safety requirements applicable to nuclear installations).

- CSN (2010b). Instrucción de seguridad IS-27 del CSN sobre criterios generales de diseño de centrales nucleares. (The Nuclear Safety Council's Instruction IS-27, of 16th June 2010, on general nuclear power plant design criteria).
- De la Garza, C. and Labarthe J.-P. (2010). Contribution to the human factors evaluation program of the EPR operating means. Some elements for discussion. In Braarud, P. Ø., Nystad, E., Strand, S., Skråning, G., Bye, A., Hildebrandt, M., and Massaiu, S. (2010). *The Halden Reactor Project Meeting on Integrated System Validation (ISV) – Status of Current Approaches to ISV and R&D Needs* (HWR-939). Halden, Norway: OECD Halden Reactor Project.
- De la Garza, C., Labarthe, J.-P. and Graglia, L. (2012). The contribution of ergonomics to risk analysis in the design process: the case of a future control room. *Work*, 41, 730-736.
- EPRI (1984). *Computer-generated display system guidelines. Volume 2: developing an evaluation plan* (EPRI NP-3701). Palo Alto, CA: EPRI.
- EPRI (2005). *Human factors guidance for control room and digital human-system interface design and modification: guidelines for planning, specification, design, licensing, implementation, training, operation and maintenance*. Palo Alto, CA: EPRI. EPRI 1010042.
- EPRI and U. S. Department of Energy (2004). *Human factors guidance for control room and digital human-system interface design and modification. Guidelines for planning, specification, design, licensing, implementation, training, operation and maintenance*. Palo Alto, CA: EPRI and Washington, D. C.: U. S. Department of Energy. EPRI 1008122.
- Forsberg, M. (2004). The Ringhals HSI and control room modernisation programme – Lessons learned. The practical application of a contemporary user and HF based HSI design process. In *Proceedings of the Man-Technology-Organisation of the Enlarged Halden Programme Group Meeting (EHPG)*, May 9-14, 2004, Sandefjord, Norway.
- Gunnarsson, T. (2007). Experiences from integrated system validation in OKG. In Braarud, P. Ø., Nystad, E., Strand, S., Skråning, G., Bye, A., Hildebrandt, M., and Massaiu, S. (2010). *The Halden Reactor Project Meeting on Integrated System Validation (ISV) – Status of Current Approaches to ISV and R&D Needs* (HWR-939). Halden, Norway: OECD Halden Reactor Project.
- Gunnarsson, T. (2007). Modernizing of Oskarshamn NPP with focus on control room issues. In *Proceedings of IAEA Technical meeting on Integrating Analog and Digital Instrumentation and Control Systems in Hybrid Main Control Rooms at Nuclear Power Plants*, October 29 - November 2, 2007, Toronto, Ontario, Canada.
- Gunnarsson, T. and Farbrot, J. E. (2005). Integrating the human factor in the modernization of Oskarshamn 1. *Eurosafe Tribune*, 15-17.
- Gunnarsson, T., Eliasson, M. (2010). The control room upgrade in Oskarshamn 2 modernization project, lesson learned from on going human factor design process. In *Proceedings of the Seventh International Topical Meeting on Nuclear Plant Instrumentation, Control and Human Machine Interface Technologies (NPIC&HMIT)*, November 7-11, 2010, Las Vegas, Nevada, USA, pp. 1812-1821.
- Gunnarsson, T., Eliasson, M. (2011). The control room upgrade in Oskarshamn 2 modernization project lesson learned from ongoing human factor design. In *Proceedings of the Man-Technology-Organisation of the Enlarged Halden Programme Group Meeting (EHPG)*, October 2-7, 2011, Sandefjord, Norway.
- Ha, J. S., Seong, P. H. (2009). A human-machine interface evaluation method: A difficulty evaluation method in information searching (DEMIS). *Reliability Engineering and System Safety*, 94, 1557–1567.

- Ha, J. S., Seong, P. H. (2010). Attentional-resource effectiveness measures in monitoring and detection tasks in nuclear power plants. *IEEE Transactions on Systems, Man, and Cybernetics – Part A: Systems and Humans*, 40(5), 993-1008.
- Ha, J. S., Seong, P. H., Lee, M. S. and Hong, J. H. (2007). Development of human performance measures for human factors validation in the advanced MCR of APR-1400. *IEEE Transactions on Nuclear Science*, 54(6), 2687-2700.
- Heimdal, J. O., Skraaning, G., and Braarud, P. Ø. (2004). *Integrated system validation: status and research needs* (HWR-754). Halden, Norway: OECD Halden Reactor Project.
- Hill, D. (2010). Halden ISV workshop. Baseline for plant modernization. In Braarud, P. Ø., Nystad, E., Strand, S., Skråning, G., Bye, A., Hildebrandt, M., and Massaiu, S. (2010). *The Halden Reactor Project Meeting on Integrated System Validation (ISV) – Status of Current Approaches to ISV and R&D Needs* (HWR-939). Halden, Norway: OECD Halden Reactor Project.
- Hill, D., Krause, W., Gunnarsson, T. (2009). The application of a human factors engineering program for major modernization project in Sweden; tools, challenges, and lessons learned from practical experiences. In *Proceedings of the Sixth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies* (NPIC&HMIT), April 5-9, 2009, Knoxville, Tennessee, USA, pp. 2440-2450.
- Hong, J. H., Lee, M. S., Hwang, D. H. (2009). Computerized procedure system for the APR1400 simulator. *Nuclear Engineering and Design*, 239, 3092–3104.
- Hwang, S.-L., Liang, S.-F. M., Liu, T.-Y. Y., Yang, Y.-J., Chen, P.-Y., Chuang, C.-F. (2009). Evaluation of human factors in interface design in main control rooms. *Nuclear Engineering and Design*, 239, 3069–3075.
- IAEA (2010). *Integration of analog and digital instrumentation and control systems in hybrid control rooms*. IAEA Nuclear Energy Series No. NP-T-3.10. Vienna: IAEA.
- IEC (1995). *Nuclear power plants – main control room – verification and validation of design* (IEC 61771). Geneva, Switzerland: International Electrical Commission.
- IEC (2009). *Design for control rooms of nuclear power plants*. IEC 964 (1989), IEC 60964 (2009). Geneva, Switzerland: International Electrical Commission.
- IEEE (2010). *IEEE guide for the application of human factors engineering to systems, equipment, and facilities of nuclear power generating stations*. IEEE-Std-1023-2004 (R2010). The Institute of Electrical and Electronics Engineers.
- IEEE (2011). *IEEE guide to evaluation of man-machine performance in nuclear power generating station control rooms and other peripheries*. IEEE-Std-845-1999 (R2011). The Institute of Electrical and Electronics Engineers.
- ISO (2006). *Ergonomic design of control centres. Part 7: principles for the evaluation of control centres*. ISO 11064. Geneva, Switzerland: ISO.
- Jiménez, A., Burillo, J. A. (2001). Verificación y validación de nuevos sistemas de apoyo a la operación para la C.N. Beznau / Verification and validation of new operation supports systems for Beznau NPP. *Nuclear España. Revista de la Sociedad Nuclear Española*, 206, 21-27.
- Jiménez, A., Burillo, J. A. (2002). Verification and validation of new operation supports systems for Beznau NPP. *Nuclear España. Revista de la Sociedad Nuclear Española*, 215.
- Kim, J. H., Ha, J. S., Ha, C. H., and Seong, P. H. (2004). Design of a human performance evaluation support system. The Seminar of JSPS-KOSEF Core University Program on Energy Science & Technology. Subtask CR04-2-2 “Advancement on Operation & Maintenance for Nuclear Power Plant”, November 1-2, 2004, Tohoku University, Sendai, Japan. http://sym-bio.jpn.org/old/reports/seminar/nikkanCUP/PDF/04_J.H.KIM.pdf

- Kloow, L. and Rydahl, I. (2004). Appendix D. Experience from successive modernization of instrumentation and control systems of Försmark 1&2. *Managing Modernization of Nuclear Power Plant Instrumentation and Control Systems* (IAEA-TECDOC-1389). Vienna, Austria: IAEA, pp. 95-103.
- Laarni, J., Koskinen, H., Salo, L., Norros, L., Braseth, N., Nurmilaukas, V. (2009). Evaluation of the Fortum IRD pilot. In *Proceedings of the Sixth American Nuclear Society International Topical Meeting on Nuclear Plant, Instrumentation, Control and Human-Machine Interface Technologies* (NPICT&HMIT), April 5-9, 2009, Knoxville, Tennessee, USA.
- Laarni, J., Norros, L., Rinttilä, E. (2007). Control room modernization from an evolutionary point of view – Experiences gained at Loviisa NPP. In *Proceedings of the Workshop on Future Control Station Designs and Human Performance Issues in Nuclear Power Plants* NEA/CSNI/R(2007)8. Paris, France: Organisation for Economic Co-operation and Development (OECD), pp. 409-429.
- Laarni, J., Savioja, P., Karvonen, H., Norros, L. (2011). Pre-validation of nuclear power plant control room design. In: D. Harris (ed.), *Engineering Psychology and Cognitive Ergonomics*, HCI 2011, pp. 404-413. Berlin: Springer-Verlag Berlin and Heidelberg GmbH & Co. K.
- Labarthe J.-P., De la Garza, C. (2011). The human factors evaluation program of a control room: the French EPR approach. *Human Factors and Ergonomics in Manufacturing & Service Industries*, 21(4), 331-349.
- Lang, A. (2007). Validation plans for a modernized main control room. In *Proceedings of IAEA Technical Meeting on Integrating Analog and Digital Instrumentation and Control Systems in Hybrid Main Control Rooms at Nuclear Power Plants*, October 29 - November 2, 2007, Toronto, Ontario, Canada.
http://entrac.iaea.org/I-and-C/TM_TORONTO_2007/Presentations/3A-TUESDAY_9-16_19-21_31/21-LANG-PRESENTATION%2021-%20Validation%20Plans%20for%20a%20Modernized%20%20.ppt#326,1,
- Lang, A. (2010). TWICE integrated HSI validation. In Braarud, P. Ø., Nystad, E., Strand, S., Skråning, G., Bye, A., Hildebrandt, M., and Massaiu, S. (2010). *The Halden Reactor Project Meeting on Integrated System Validation (ISV) – Status of Current Approaches to ISV and R&D Needs* (HWR-939). Halden, Norway: OECD Halden Reactor Project.
- Lang, A. W. (2009). Preparing for the validation of a modernized main control room. In *Proceedings of the Sixth American Nuclear Society International Topical Meeting on Nuclear Plant, Instrumentation, Control and Human-Machine Interface Technologies* (NPICT&HMIT), April 5-9, 2009, Knoxville, Tennessee, USA, pp. 2402-2407.
- Lang, A. W., Roth, E. M., Bladh, K., Hine, R. (2002). Using a benchmark-referenced approach for validating a power plant control room: results of the baseline study. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 5, pp. 1878-1882.
- Lee, C.-M., Tsai, W.-C., Wong, K. W. and Pang, T. (2009). The new generation nuclear power plant simulator – The Lungmen ABWR simulator. In *Proceedings of the Sixth American Nuclear Society International Topical Meeting on Nuclear Plant, Instrumentation, Control and Human-Machine Interface Technologies* (NPICT&HMIT), April 5-9, 2009, Knoxville, Tennessee, USA, pp. 2202-2213.
- Lee, D. H., Jeong, C. H., Go, J. S. (2007). Regulatory issues of new control room design: a case study of Shin-Kori 3 and 4 nuclear power plants. In *Proceedings of the Workshop on Future Control Station Designs and Human Performance Issues in Nuclear Power Plants*. NEA/CSNI/R(2007)8. Paris, France: Organisation for Economic Co-operation and Development (OECD), pp. 447-460.

- Lee, D. H., Kim, D. I., Chung, C. H. (2007). Regulatory approach on human factors engineering of main control room modernization: a case of Kori-1 nuclear power plant in Korea. In *Proceedings of Joint 8th IEEE Human Factors and Power Plants (HFPP) / 13th Human Performance / Root Cause / Trending / Operating Experience / and Self Assessment (HPRCT)*, August 26-31, 2007, Monterey, California, USA.
- Lee, J. W., Oh, I. S., Cheon, S. W., Chung, Y. H., and Lee, J. H. (1999). Human factors review guide for Korean next generation reactor. *Transactions of the 15th International Conference on Structural Mechanics in Reactor Technology (SMIRT-15)*, August 15-29, 1999, Seoul, Korea, XI-353 – XI-360.
- Lee, M. S., Hong, J. H., Suh, J. K., Lee, S. H., Hwang, D. H. (2009). Development of human factors validation system for the advanced control room of APR1400. *Journal of Nuclear Science and Technology*, 46(1), 90–101.
- Lin, C. J., Jou, Y.-T., Yenn, T.-C., Hsieh, T.-L. and Yang, C.-W. (2009). A study of control room staffing and workload from the human information processing perspective. In *Proceedings of the 2009 IEEE International Conference on Networking, Sensing and Control*, March 26-29, 2009, Okayama, Japan, pp. 303-307.
- Miberg-Skjerve, A. B., Skraaning Jr., G. (2004). A classification of validation criteria for new operational design concepts in nuclear process control. In *Proceedings of the CSNI WGOE/SEGHOE Workshop on Modifications at Nuclear Power Plants - Operating Experience, Safety Significance and the Role of Human Factors and Organisation*. NEA/CSNI/R(2004)17. Paris, France: Organisation for Economic Co-operation and Development (OECD), pp. 117-129.
- NEA/CSNI/R(2005)10. *Safety of modifications at nuclear power plants. The role of minor modifications and human and organisational factors. Appendix 7. One example of instructions for incorporating human factors in a modification process*. Paris, France: Organisation for Economic Co-operation and Development (OECD), pp. 79-87.
- Norros, L. (2004). *Acting under uncertainty. The core-task analysis in ecological study of work*. VTT publications 546. Espoo, Finland: VTT Technical Research Centre of Finland. 241 pp. <http://www.vtt.fi/inf/pdf/publications/2004/P546.pdf>
- Norros, L. and Savioja, P. (2005). Validation of NPP control rooms: new HF assessment methods. *Eurosafe Tribune*, 12-14.
- Norros, L. and Savioja, P. (2004). Modeling the activity system – development of an evaluation method for integrated system validation. In *Proceedings of the Man-Technology-Organisation of the Enlarged Halden Programme Group Meeting (EHPG)*, May 9-14, 2004, Sandefjord, Norway.
- Norros, L., Koskinen, H., Hildebrandt, M., Paulus, V., Gauthier, B., Origin, A. (2011). Methodology for evaluation of innovative concepts: case FITNESS control station concept. In *Proceedings of the Man-Technology-Organisation of the Enlarged Halden Programme Group Meeting (EHPG)*, October 2-7, 2011, Sandefjord, Norway.
- Norros, L., Liinasuo, M., Hutton, R. (2011). Evaluating the potential of new technological tools for safety critical work. *Interacting with computers*, 23, 299-307.
- Norros, L., Nuutinen, M. (2005). Performance-based usability evaluation of a safety information and alarm system. *International Journal of Human-Computer Studies*, 63, 328-361.
- Norros, L., Savioja, P. (2004). *Usability evaluation of complex systems. A literature review*. STUK-YTO-TR 204. Helsinki, Finland: STUK. 44 pp.
- Norros, L., Savioja, P. (2005). Theoretical justification of performance indicators for integrated validation of complex systems. In *Proceedings of the Man-Technology-*

- Organisation of the Enlarged Halden Programme Group Meeting (EHPG)*, October 17-21, 2005, Lillehammer, Norway.
- Norros, L., Savioja, P. (2007). Towards a theory and method for usability evaluation of complex human-technology systems. *Activités*, 4(2), 143-150.
 - Norros, L., Savioja, P., Salo, L. (2009). Approach to integrated system validation of NPP control rooms. In *Proceedings of the Sixth American Nuclear Society International Topical Meeting on Nuclear Plant, Instrumentation, Control and Human-Machine Interface Technologies* (NPIC&HMIT), April 5-9, 2009, Knoxville, Tennessee, USA, pp. 1998-2010.
 - NRC (2004). *Human system interface design review guideline* (NUREG-0700). Rev. 0 (1981), Rev. 1 (1996), Rev. 2 (2004). Washington, D. C.: U. S. Nuclear Regulatory Commission.
 - NRC (2007). *Standard review plan for the review of safety analysis reports for nuclear power plants. Chapter 18. Human factors engineering* (NUREG-0800). Rev. 0 (1996), Rev. 1 (2004), Rev. 2 (2007). Washington, D.C.: U.S. Nuclear Regulatory Commission.
 - NRC (2012). *Human factors program review model* (NUREG-0711). Rev. 0 (1994), Rev. 1 (2002), Rev. 2 (2004), Rev. 3 (2012). Washington, D. C.: U. S. Nuclear Regulatory Commission.
 - NRC (2007). *Guidance for the review of changes to human action* (NUREG-1764). Rev. 0 (2004), Rev. 1 (2007). Washington, D.C.: U.S. Nuclear Regulatory Commission.
 - Nuutinen, M., Norros, L. (2009). Core task analysis in accident investigation: analysis of maritime accidents in piloting situations. *Cognition, Technology and Work*, 11, 129-150.
 - O'Hara J., Gunther, W., and Martínez-Guridi, G. (2010). *The effects of degraded digital instrumentation and control systems on human-system interfaces and operator performance* (BNL Tech Report No. 910472010). Upton, NY: Brookhaven National Laboratory.
 - O'Hara, J. (1994). *Advanced human-system interface design review guideline. General evaluation model, technical development, and guideline description* (Volume 1). *Evaluation procedures and guidelines for human factors engineering reviews* (Volume 2) (NUREG/CR-5908). Washington, D. C.: U. S. Nuclear Regulatory Commission.
 - O'Hara, J. (2009). *Applying human performance models to designing and evaluating nuclear power plants: review guidance and technical basis* (BNL Technical Report BNL-90676-2009). Upton, NY: Brookhaven National Laboratory.
 - O'Hara, J., Higgins, J. and Fleger, S. (2011). Updating human factors engineering guidelines for conducting safety reviews of nuclear power plants. In *Proceedings of the 55th Annual Meeting of the Human Factors and Ergonomics Society*, September 19-23, 2011, Las Vegas, Nevada, USA.
 - O'Hara, J., Higgins, J. and Fleger, S. (2012). Human factors engineering program review model (NUREG-0711) revision 3: update methodology and key revisions. In *Proceedings of the Eighth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies* (NPIC&HMIT), July 22–26, 2012, San Diego, CA, USA.
 - O'Hara, J., Stubler, W., Higgins, J. C. and Brown, W. (1997). *Integrated system validation: methodology and review criteria* (NUREG/CR-6393). Washington, D. C.: U. S. Nuclear Regulatory Commission.
 - Ohlson, E. (2009). TIGER - A method for incorporating human factors into NPP modernizations. In *Proceedings of the Sixth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies* (NPIC&HMIT), April 5-9, 2009, Knoxville, Tennessee, USA, pp. 2430-2439.

- Savioja, P. and Norros, L. (2004). Evaluation of operator practices as a means of integrated system validation. In *Proceedings of the Fourth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human Machine Interface Technology* (NPICT&HMIT), September 19-22, 2004, Columbus, Ohio, USA.
- Savioja, P. Norros, L. Salo, L. Kivikunnas, S. and Karppinen, J. (2005). Core-task analysis in requirements gathering for an adaptive batch process control interface. In *Proceedings of the Annual Conference of the European Association of Cognitive Ergonomics*, September 29 - October 1, 2005, Crete, Greece, pp. 19-25.
- Savioja, P., Norros, L. (2008). Systems usability – promoting core-task oriented work practices. In: E. Law, E. T. Hvannberg, G. Cocton (eds.), *Maturing usability: quality in software, interaction and value*, pp. 123-143. London: Springer.
- Savioja, P., Norros, L., Salo, L., Laarni, J., Liinasuo, M. (2010). Integrated system validation: the questions of independence and reference. In *Proceedings of the Man-Technology-Organisation of the Enlarged Halden Programme Group Meeting* (EHPG), March 14-19, 2010, Storefjell, Norway.
- Skraaning G., Braarud, P. Ø. and Heimdal, J. O. (2004). A calibration approach to integrated system validation. In *Proceedings of Fourth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Controls and Human-Machine Interface Technologies* (NPIC&HMIT), September 19-22, 2004, Columbus, Ohio, USA.
- Trueba Alonso, P., Fernández Illobre, L., Jiménez Fernández-Sesma, A., Ortega Pascual, F. (2008). Human factors verification and validation: Tecnatom's experience. In *Proceedings of the 16th International Conference on Nuclear Engineering* (ICONE16), May 11-15, 2008, Orlando, Florida, USA, pp. 209-216.
- Trueba Alonso, P., Fernández Illobre, L., Jiménez Fernández-Sesma, A. (2008). Verificación y validación de factores humanos, su presencia como elemento 10 del NUREG-0711 y la experiencia de Tecnatom en su aplicación. In *Proceedings of 34th Reunión Anual de la Sociedad Nuclear Española* (SNE), October 29-31, 2008, Murcia, Spain.
- Westinghouse Electric Company (2002). Modernization: bringing a plant up-to-date. *Westinghouse World View*, 6-7.

