Nordisk kernesikkerhedsforskning
Norrænar kjarnöryggisrannsóknir
Pohjoismainen ydinturvallisuustutkimus
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Nordic nuclear safety research

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Human Reliability Guidance - How to Increase the Synergies Between Human Reliability, Human Factors, and System Design & Engineering.

Phase 2: The American Point of View - Insights of How the US nuclear Industry Works With Human Reliability Analysis

Johanna Oxstrand

Vattenfall Ringhals AB

December 2010

Abstract

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nuclear industries, and to find data regarding the findings from the first study. The main focus of this report is to identify potential HRA improvements based on the data collected in the American Point of View survey.

Key words

human reliability analysis; design; nuclear power plant

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Keywords—*human reliability analysis; design; nuclear power plant*

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I. Introduction to Human Reliability Analysis and Human Factors

A. History of Human Reliability Analysis

Human reliability analysis (HRA) is a tool to predict human performance probabilistically that originated as a subfield to human factors. HRA had a strong connection to risk analysis from the beginning. HRA was developed to predict potential human errors as a supplement to the risk analysis of the system and equipment. The human factors field, in contrast, has a diagnostic focus, and one could view the predictive nature of the HRA as filling a void in the human factors field [1]. HRA has reatined its predictive nature and is still used to analyze how systems might degrade as a result of human performance.

The development of the human factors field has mirrored the development of society. Human factors is today involved in consumer products and in industry applications, but it began by providing design guidance for military applications. Human factors covers anything from the design of pencils, ergonomics, and usability tests, to design guidelines. The main focus of HRA, on the other hand, has been safety-critical applications for which human error has the potential for severe consequences. Therefore, HRA has remained closely associated with industries that employ complex systems. HRA has in particular been closely aligned with the nuclear industry and this has been the case since the 1980s. The first documented method used to conduct HRA was A Technique for Human Error Rate Prediction (THERP), which was authored by Swain and Guttman and published by the NRC in 1983 [2]. Since the development of THERP, a wide range of other HRA methods have appeared.

HRA can be used for different applications – to support the licensing of a plant, to verify plant modernization and upgrades, and in support of risk-informed decision making. The focus HRA gets in the nuclear industry might differ between countries. Potentially, this could be a function of the amount of time spent working in the field. One of the purposes of the *Human Reliability Guidance* project was to explore what a nuclear industry that has not extensively used HRA – the Nordic nuclear industry – might learn from a nuclear industry that has a long history of HRA applications – the American nuclear industry. The American Point of View study takes these lessons learned and extrapolates them to general improvement of the HRA field. The *Human Reliability Guidance* project is described in more detail in section *II-The Nordic Nuclear Safety Research Project – Human Reliability Guidance.*

B. Introduction to U.S. Nuclear Regulatory Commission's Departments

One of the main focuses in the American Point of View part of the *Human Reliability Guidance* project (described in section *II-The Nordic Nuclear Safety Research Project – Human Reliability Guidance*) is to provide an understanding of how the American nuclear regulatory body and the nuclear industry use HRA. This section provides a short summary of the different organizations within the U.S. Nuclear Regulatory Commission (NRC) that are participating in this survey, and their different responsibilities. In this part of the study, 13 employees from three different NRC organizations were interviewed. The organizations represented are the Office of Nuclear Regulatory Research (RES), the Office of Nuclear Reactor Regulation (NRR), and the Technical Training Center (TTC). The information quoted below is from the NRC's official website – www.nrc.gov.

1) Office of Nuclear Regulatory Research

"[The Office of Nuclear Regulatory Research (RES)] provides leadership and plans, recommends, manages and implements programs of nuclear regulatory research, and interfaces with all NRC Offices and the Commission on research issues. Independently proposes improvements to the agency's regulatory research programs and processes to achieve enhanced safety, efficiency and/or effectiveness based on the results of this research. Coordinates research activities with the Program Offices, as appropriate. Coordinates the development of consensus and voluntary standards for agency use, including appointment of RES staff to committees. Based on research results and experience gained, recommends regulatory actions to resolve ongoing and potential safety issues for nuclear power plants and other facilities regulated by the NRC, including those issues designated as Generic Safety Issues (GSIs). Conducts research to reduce uncertainties in areas of potentially high safety or security risk or significance. Develops the technical basis for risk-informed, performance-based regulations in all areas regulated by the NRC. Leads the agency's initiative for cooperative research with the U.S. Department of Energy (DOE) and other Federal agencies, the domestic nuclear industry, U.S. universities, and international partners. Coordinates research activities outside the agency, including appointment of RES staff to domestic and international committees and conferences. Maintains technical capability to develop information for resolution of nuclear safety and security issues and provides technical support and consultation to the Program Offices in the specialized disciplines involved in these issues. Provides independent analysis of operational data and assessment of operational experience through the review, analysis, and evaluation of the safety performance of facilities licensed by the NRC. Collects and analyzes operational data; assesses trends in performance from this data; evaluates operating experience to provide insights into and improve the understanding of the risk significance of events, precursors and trends; and, produces and disseminates periodic performance indicator and Accident Sequence Precursor (ASP) Reports. Provides program direction, coordination, and implementation for homeland security research. Provides administrative and technical support for the Committee to Review Generic Requirements (CRGR)." [3]

2) **Office of Nuclear Reactor Regulation**

"[The Office of Nuclear Reactor Regulation (NRR)] is responsible for accomplishing key components of the NRC's nuclear reactor safety mission. As such, NRR conducts a broad range of regulatory activities in the four primary program areas of rulemaking, licensing, oversight, and incident response for commercial nuclear power reactors, and test and research reactors to protect the public health, safety, and the environment" [4]

3) **Technical Training Center**

"[The Reactor Technology Training branches at the Technical Training Center] designs, develops, maintains, improves, and implements a reactor technology curriculum in each of the General Electric, Westinghouse, Combustion Engineering, and Babcock and Wilcox reactor vendor designs based on integrated agency needs. Provides a spectrum of classroom and full scope simulator courses to meet the cumulative reactor technology and regulatory skills training needs of the NRC inspection staff. Provides training to develop and maintain agency skills related to performance-based regulatory safety assessment of control room configuration, integrated plant operation, and application of emergency operating procedures, severe accident guidelines, and emergency procedure guidelines. Develops new courses and modifies existing courses to meet new or changing needs. Provides information, assistance, and counsel to employees on career development. Ensures reactor technology training activities align with the agency Strategic Plan and the Training and Development Strategic Plan. Provides expert technical assistance to NRC, other government agencies, and foreign regulatory agencies on reactor operations, regulatory programs, human resources development, and training systems methodology and standards" [5].

II. The Nordic Nuclear Safety Research Project – Human Reliability Guidance

A. Background

The Nordic Nuclear Safety Research (NKS) council and Vattenfall Ringhals AB are sponsoring the current project, Human Reliability Guidance – How to Increase the Synergies between Human Reliability, Human Factors, and System Design & Engineering (NKS Project Code: NKS_R_2009_77).

The purpose of the Human Reliability Guidance project is to work across the borders of human factors, Human-System Interaction (HSI), Probabilistic Risk Assessment (PRA), and Human Reliability Analysis (HRA) that exist today. The author anticipates that one of the long-term effects of the project will be to diminish these borders between the disciplines. Each discipline does great work individually, but without the full collaborative picture they may not be able to determine the most suitable solution to manage the overall risk at nuclear power plants.

The nuclear industry is experiencing a renaissance when it comes to human factors and human reliability. The Swedish nuclear industry and the Swedish Nuclear Radiation Safety Authority (SSM), for example, want to gain more knowledge about how to, in a suitable and effective way, address the issue of human factors in control room modernizations and upgrades. This quest for knowledge was the main driving factor for the Oxstrand and Boring user needs analysis [6].

The original goal of the Human Reliability Guidance project was to produce guidance for how to use HRA to strengthen overall safety. This guidance should cover how to establish communication between HRA work and other disciplines, such as human factors and system design and engineering. This guidance should aim to both reconcile disparities between disciplines and within the HRA and PRA communities. As a natural part of the project, process sub-goals have evolved, one for each of the project's sub-studies. The sub-goals are intended to produce guidance to improve the system design process by using HRA, and produce guidance on how to improve the HRA field itself. As a long-term goal, the work should result in a positive change in the way human factors and HRA are thought of and worked with in the Nordic nuclear industry.

The project consists of two sub-studies: *The Nordic Point of View – A User Needs Analysis,* and *The American Point of View – Insights on How the US Nuclear Industry Works with HRA.* The purpose of the Nordic Point of View study was a user needs analysis that aimed to survey current practices of HRA in the Nordic nuclear industry, with the main focus being to bridge HRA and system design. In this study, 26 Nordic (Swedish and Finnish) nuclear power plant specialists, with research, practitioner, and regulatory expertise in HRA, PRA, HSI, and human performance were interviewed. This study was completed in 2009 [6-8]. The authors of the Nordic Point of View study, Oxstrand and Boring, argue that HRA is an important tool when dealing with human factors in control room design or modernizations [6].

The Nordic Point of View study showed areas where the use of HRA in the Nordic nuclear industry could be improved. To gain more knowledge about how these improvements could be made, and what improvements to focus on, the second study was conducted. The second study is focused on the American nuclear industry, which has many more years of experience with PRA and HRA than the Nordic nuclear industry. Interviews were conducted to collect information to help the author understand the similarities and differences between the American and the Nordic nuclear industries, and to find data corroborating the findings from the first study. The preliminary comparison between the Nordic and the American nuclear industries use of HRA were presented at the Enlarged Halden Programme Group meeting 2010 [9]. The main focus of this report is to identify potential HRA improvements based on the data collected in the American Point of View survey.

B. Current Research Project: The American Point of View

1) Purpose and Aim

The purpose of the survey conducted in the American Point of View part of the Human Reliability Guidance project was to understand how the American nuclear industry and regulatory authority work with HRA, and to gain more knowledge about potential improvements needed within the HRA field. The Nordic industry relies heavily on American HRA research and guidance documents, which made it important to incorporate this information into the Human Reliability Guidance project.

The aim of the American Point of View study was to produce guidance on how to improve the field of HRA and to incorporate this guidance, along with the ten principles provided in the output from the Nordic Point of View study [6].

2) Method and Participants

The method used for the American Point of View study was informal semi- structured interviews, using a protocol of high-level questions. The interviews centered on the practice of HRA today, what needs to be improved, and what are the main strengths and limitations of conducting the analyses. There was also a focus on the relationship between HRA and human factors, the relationship between HRA and PRA, and if and how these relationships could be improved. The majority of the interviews were conducted via telephone, but a few of the interviews were conducted in person. All interviews were recorded, mainly to ensure that the author did not miss any valuable information due to a potential language barrier, as the interviews were not conducted in the author’s native tongue.

The following questions are the most important ones, in the sense of being good sources of data for informing the usage of HRA and the interaction between HRA, PRA, and human factors:

- How is HRA used in the nuclear industry?
- How does the NRC work with HRA?
- What is the relationship between HRA and PRA?
- What is the relationship between HRA and human factors?

Some questions that were used in the first study of the Human Reliability Guidance project recurred in the survey conducted in the American Point of View part of the project. These questions were:

- What are the barriers to HRA being used more?
- What are the main strengths of HRA in your view?
- What are the main weaknesses of HRA in your view?

Additional questions centered on providing background on the job functions and responsibilities of each specialist. The results summarized in this report represent mainly the relevant findings of how the American nuclear industry and regulatory authority might use HRA, and what insights and findings could be helpful to improve the Nordic nuclear industry usage of HRA.

In the survey conducted for the American Point of View part of the Human Reliability Guidance project, 31 interviews with HRA, PRA, and human performance expertise within the nuclear industry were held. Table 1 shows the distribution of the participants related to their current employment. Employees interviewed at Sandia National Laboratories and Idaho National Laboratory are represented in the National Labs group. This group supports HRA and PRA efforts at the US Nuclear Regulatory Commission (NRC). NRC employees at the Office of Nuclear Regulatory Research (RES), Office of Nuclear Reactor Regulation (NRR), and the Technical Training Center (TTC) are represented in the NRC group. Contractors that conduct HRA work for the nuclear utilities are represented in the Industry group.

To ensure the anonymity of the participants, the level of background detail provided here regarding the individuals is purposefully kept low.

TABLE 1. NUMBERS OF INTERVIEWEES AND THEIR TYPE OF EMPLOYMENT

Current Employment	Total Participants
National Labs	12
US NRC	13
Industry	6
Total	31

By looking at all participating interviewees in the *Human Reliability Guidanc*e project (both the Nordic and the American study) one will find that about 78% of the Nordic participants have an engineering background, while about 95% of the American participants have a background in psychology. The participants in the Nordic Point of View study were the vast majority of the Nordic HRA population in the Nordic countries that have nuclear power. It is interesting to note that while there is substantial HRA research conducted at the Institute for Energy Technology (IFE) in Norway, no Norwegians participated in this study. If a follow-on study were to be conducted it would most certainly be of interest to interview the Norwegian HRA population as well. IFE acts as research consultants for most of the Nordic nuclear power plants. Many of the Nordic participants in the Nordic Point of View study are involved in the research conducted by IFE and have good insights into the current Nordic HRA research. Therefore, the author is confident that even though many of the Nordic participants have an engineering background, the research aspects are still covered to a reasonable extent.

The reason that the vast majority of interviewees in the American Point of View study have a psychological background is that most American researchers involved in the HRA field have a degree in psychology or closely related discipline. This study focused on HRA researchers in the USA rather than HRA practitioners and hence the high number of participants with a psychological background. The author highly recommends incorporating more HRA practitioners in future studies, who anecdotally seem to have more of a background in engineering than the HRA research community. The main focus of the American Point of View study was to find areas of improvements in the HRA field. Therefore, the national laboratories and the NRC were natural survey points. There were also some security issues with interviewing people at nuclear power plants due to the author not being an American citizen.

One may discuss whether the outcome of American Point of View study would have been different if there were more participants who worked in the nuclear industry or had an engineering background. Many of the interviewees that currently are employed by the NRC have long histories working with PRA, HRA, or human factors in the nuclear industry. This, combined with the participation by the industry, assures the author that the industry perspective is reflected in the study. Clearly, it would be interesting to do a follow-on study with a greater industry focus to see how the outcome from this study could be made more reflective of industry's needs and perspectives.

3) Data Analysis

The data collected during the interviews were analyzed and summarized with the objective to catalog the findings according to common themes. The catalog of interview data was developed by categorizing the data according to the different fields of interest, based on the ten principles from the previous study (the Nordic Point of View). Additional categories were also added when needed. Both the face-to-face interviews and the interviews conducted via telephone were recorded, and one analyst reviewed these recordings and notes to capture insights. An additional analyst did attend a few of the interview sessions to make sure that no valuable information would get lost in translation, since the interviews were not conducted in the main analyst's native tongue. The findings were aggregated into a single set of findings. While conducting the data analysis and categorizing of data, the author's own subjectivity was inserted into the process. Therefore, the result of the data analysis will be presented in conjunction with the author's discussion. A few caveats are necessary to understand the findings captured from the interviews.

- In most cases, the findings represent remarks made by more than a single interviewee. However, relevant comments made by a single interviewee are also presented below for the sake of capturing a wide range of thoughts regarding the use of HRA – especially regarding the future of the field.

- The discussion in this report does not point out the specific findings. If access to the raw data is desired, please contact the author.

- In order to preserve the anonymity of the interviewees, the findings below are not attributed to specific people.

- The views expressed should be considered those of individuals and should not necessarily be assumed to reflect official views of the NRC or national laboratories.

III. Discussion of the findings

The analyzed data and discussion are presented in this section. First, a general description of HRA is provided, followed by information on the use of HRA at the U.S. Nuclear Regulatory Commission and in the commercial nuclear power industry. The need for the organizations to see a return on HRA investments is also discussed. Then the differences and similarities between the use of HRA in the American and Nordic nuclear industry are described. To understand why HRA is used the way it is today, the relationships between HRA and human factors and between HRA and PRA are explored. These discussions are based on the interviews and reflect views expressed by the interviewees. One of the purposes of the study was to investigate the potential areas for improvements to HRA. The future of HRA is discussed in the sense of method development, data collection, communication, use of HRA in design, use of HRA outside PRA, and use of HRA outside the nuclear domain. This information elaborates upon the principles presented in section *IV - Principles for Human Reliability Analysis*.

A. General Description of Human Reliability Analysis

Human reliability analysis (HRA) offers insights into the most variable system of all – the human. Within the nuclear industry there is an acceptance that HRA is something that needs to be conducted in order to fully understand operational risk. People need to know that they are working on an important piece of equipment. If not, safety will be reduced at the plant because the equipment being worked on might be needed to mitigate an accident. Risk and human reliability need to be incorporated into the way we view safety at the nuclear power plant, just like equipment reliability. There is a need to better understand both how complex systems fail, and how they can succeed and be effective. There is also a need for a predictive analysis of how complex systems can fail in order to predict (and thus address) the factors that contribute to failure.

HRA helps people appreciate the types of issues that are important to human operated systems and human reliability with respect to these systems. In terms of searching for vulnerabilities and understanding how things can go wrong, HRA is a useful tool. HRA fosters an analytic mindset based on evidence and careful reasoning. HRA helps people focus on what can go wrong and what can be done in terms of prevention. HRA also provides a standardized methodology. In the case where a qualitative analysis has been conducted, and then quantified with data or other information, the analysis becomes a bridge between the method and observed events. This is very insightful. An HRA conducted correctly, employing an integrated multidisciplinary team with sufficient resources, i.e. doing the HRA according to the Good Practices [15], will produce useful qualitative insights about how the human component (the operator) is being set up for failure. The strength of HRA is to utilize the information gained from this analysis, and recognize that this information is important.

Both PRA and HRA derive from the industry's need to do risk analysis, and both of them are technologies used to quantitatively identify the kinds of hazards that are present in a system or in an operation. They are also a way to estimate the quantitative risk metrics that are important to safety of that system, and to prioritize the importance of human actions and hardware responses. PRA and HRA are being recognized as tools to analyze risk probabilistically and they are used by the utilities for various applications, such as risk-informed decision making regarding changes to the plant's licensing basis, and in evaluation of inspection findings via the significance determination process (SDP). In the SDP, HRA is used to evaluate operator performance when events occur, i.e., HRA is an input to the risk assessment performed to determine the significance of a finding. HRA is used to analyze the human contribution to safety and risk in the utilities and is primarily used to support error identification, error organization and modeling, and human error quantification as a part of the utilities' licensing submissions.

As a part of the PRA, the human role in the analyzed scenarios needs to be evaluated. HRA is used to conduct this evaluation, i.e., HRA is an input to the overall PRA that is conducted for plants' baseline PRA. HRA has been developed as a mean to estimate the role of human performance and its impact on bottom-line risk. HRA has two main components: 1) to understand the accidents and the equipment performance for the human actions modeled, and 2) to understand human performance given those situations, which depends on the human-machine interface at the plant, the scenario, the procedures, the plant performance, the team interaction, etc.

The operator's situation can be improved through the process of HRA since exposing weaknesses is the strength of this type of analysis. HRA is a great tool for identifying vulnerabilities in the system. When the vulnerabilities are identified, barriers can be put in place to prevent human errors from occurring. Each time a problem arises at a utility it is analyzed to find potential human performance issues, and to find out how these potential issues could be resolved and prevented from happening again. The intent behind HRA is to identify the serious vulnerabilities in the system, and also to identify areas of weakness where human performance needs to be improved. These insights could be addressed by reviewing procedures, training, plant modifications, etc. If applied correctly, HRA will help identify risk scenarios, including risk scenarios involving human-system interactions. This improves the quality of the PRA and it may also help prioritize the sequences that will go into operator training.

In order to conduct a quality analysis it is important to have good knowledge about all the aspects you are analyzing. Therefore, a human factors analyst or a human reliability analyst should be trained on whatever technology they are analyzing. Engineers that are applying human factors or human reliability techniques need to have training in these fields in order to apply the techniques correctly. It is sometimes hard to make people understand why this is important. There is perhaps a grudging acceptance of human factors amongst the engineering community. The engineers believe there is a need for human factors, but they do not necessarily understand it.

The importance of operator interviews while conducting an analysis should be emphasized. *Interviews and plant visits are the only way to get a true understanding of the scenario, which is important to get realistic or best estimates.* This importance will only increase for the new reactors that are currently being planned and built, because the demands on the operators are going to be very different in the future. Even though the operators will face new demands, building new reactors can also be viewed as a positive change. Today we are experiencing a degradation in operator knowledge in each new generation, because they are further away from the time of hands-on work building the plants. The new-generation operators that take over from the older generation lack hands-on experience with the technology.

Human performance is emphasized at the utilities, and the importance of good performance is recognized. The emphasis is to identify, resolve, and prevent human performance issues from occurring in the first place. The utilities have been good at understanding the principal implications of working with (or not working enough with) human performance – both preventive and reactive. This is partly due to an increased understanding of how to manage the insights the HRA provides. The main human performance issue in the nuclear industry is that a large nuclear plant is such a complex system, and it is hard to train the operators to be prepared for every potential situation. It is also a challenge to train the operators to know when they should use their knowledge versus strictly following procedures. Thus, the operators need to have the ability to recognize when the procedures are not compatible with the actual scenario and what is required to keep the plant safe in such an event. A variety of human performance tools exist that are intended to help reduce the risk of human error, but it is sometimes hard to retrain operators to use these tools, because using the tool can sometimes actually make a task more complicated to perform. It is therefore very important to make sure to keep a good balance between the number of tools provided and the actual time available to perform a task.

B. Usage of Human Reliability Analysis by the Regulatory Body and the Nuclear Industry

The NRC uses PRA and HRA to support the regulatory process and to understand different kinds of risks quantitatively. They use HRA both as a method and as a tool to assess licensee (utility) performance, as well as their documents and safety basis. The main drivers for the regulator's use of PRA and HRA are given by Reg.Guide 1.200 [10] which provides guidelines on the acceptability of the PRA, and hence also for the HRA. Both the NRC and the industry are trying to find ways to use PRA and HRA more in decision making. Generally, the guidance documents talk about conducting a PRA in the context of supporting a decision.

PRA is a regulatory tool to evaluate whether the plants meet certain criteria. The U.S. Nuclear Regulatory Commission (NRC) reactor oversight process (ROP) involves retrospective analysis, which has a strong human factors component. This process supports the regulator and industry in their decision making. If the performance indicators or inspections begin to show a declining trend, the NRC will ramp up the inspection process in a predefined manner to try to get a good sense of the root cause of the decline in performances.

The NRC issued a policy statement in 1995 that basically said that PRA should be used as much as possible in all regulatory activities within the limitations of the state-of-the-art [11]. This is a statement of NRC's intentions. The NRC oversees the requirements for how to conduct HRA and provides guidance for reviewing HRA and on how to perform a HRA.

The NRC inspectors use Procedure 0612 [12] to determine if an observation constitutes a performance deficiency. If the requirements of this procedure are met, a performance deficiency is assigned. The NRC regional offices perform most of the analyses, and the NRC headquarters staff review them. If it's a shutdown issue, headquarters conducts the analysis. To understand the issue at hand, the NRC talks to operators, goes to the site, etc. All of this is guided by procedures. The result from the evaluation is presented to the agency, and then the plant has the opportunity to present additional information that the NRC might need to consider. The plant may also think about short-term actions to minimize the risk change. This could be new evidence based on simulator runs. If the NRC agrees with the new information they can change their determination of significance of the issue.

As described above, PRA and HRA are used in supporting a determination of the significance of various inspection findings. The PRA and HRA are also used by the NRC to identify the seriousness of an actual event that has transpired. This evaluation of events at a plant is also part of the SDP, and PRA and HRA are parts of this evaluation. When an event (e.g. component failure) has occurred at a nuclear power plant, this is reported to the NRC. The NRC then determines what the situation is. The NRC staff investigates the risk significant of events utilizing a Standardized Plant Analysis Risk (SPAR) model. The SPAR models are PRA models of the commercial nuclear power plants in the US that are used for the enforcement process, event assessment, generic safety issues program, etc. The NRC has 77 of these SPAR models that cover the 104 reactors in the US. The SPAR model will determine the probability of the failure and also the probability of human failure. The SPAR-models are the most apparent way the NRC uses HRA. The utilities maintain their own HRA and PRA models, and the NRC maintains its models. The NRC needs to keep their own models because they conduct independent analyses. Since the utilities have plant-specific models, their models are more detailed than the NRC's SPAR models.

The NRC uses the SPAR-H HRA method [13] to conduct the HRA for its PRA evaluations. The PRA group runs the model with the failed component and the potential human failure event to estimate the resulting change in risk, for which the change in core damage frequency is calculated surrogate. About 70% of all the failures at the utility are due to human performance, i.e., the errors are human-induced. Hence, HRA is an important part of the significance determination process.

The focus for the HRA work at the Office of Nuclear Regulatory Research (RES) is to provide a good technical basis for reviewing HRA that is part of licensees' submissions for various applications. RES works to improve the empirical basis of human error probabilities, and support research into areas that are not covered by the Good Practices [15], such as Errors of Commission.

The Probabilistic Risk Assessment branch at RES develops and revises regulatory guidance associated with the use of risk in the regulatory licensing process. The Probabilistic Risk Assessment branch at RES comprises approximately ten staff members in total, who are basically tasked with developing and managing risk methods, models, and tools for the NRC's regulatory process. The branch is directly involved in developing some of the tools involved in that process. The Probabilistic Risk Assessment branch at RES tries to advance the state-of-the-art in PRA. They look at dynamic PRA, better integration between Level 1-2 and Level 2-3 PRA, low power shutdown work, regulatory guidance development, and they also support digital I&C PRA research to try to determine ways to model digital I&C systems in PRAs. They obviously have to work very closely with the Human Factors and Reliability branch. This branch is located in the same division in RES.

The Technical Training Center (TTC) provides the inspectors with the basic knowledge necessary to do an adequate job at the commercial nuclear facilities in the US. The main purpose of the TTC is to train NRC residents and inspector staff at the regional offices who are involved in inspections of commercial nuclear power plants. The human factors staff at NRC sometimes uses the TTC simulators to run various studies.

The NRC provides limited training on HRA to risk analysts, which is a theoretical and philosophical course. A more practical course that is tailored to use of the SPAR-models and the SPAR-H HRA method is under development.

The US commercial nuclear power industry uses PRA to determine how to best run a particular type of evolution and in support of SDP evaluations. All - or nearly all - utilities are using the EPRI HRA calculator for their HRA applications. EPRI, thru Scientech, develops and maintains the HRA calculator, which is designed to meet all ANS/ASME standard requirements for HRA. The industry is very reliant on the EPRI calculator. The industry mainly uses HRA to produce human error probabilities required by the PRA, and therefore desires a method that is easy to apply and easy to understand. Even though a lot of HRA development has been done, the industry still relies heavily on the methods in the EPRI calculator. Because there are several dozen existing HRA methods, a part of the HRA research community is pushing to find which method (or combination of methods, perhaps with enhancements) is the best one to use. By relying on the EPRI HRA calculator, the industry has effectively downselected the HRA methods contained in the Calculator (primarily HCR, CBDT, and THERP). The HRA community just has not decided if these are the most appropriate methods to use. The utilities use methods or tools that are easily available or those endorsed by the regulator. The EPRI HRA calculator happens to fit these requirements.

Industry uses PRA and HRA for risk-informed decision making. The combination is usually used to support answering questions such as: Is it better to do option A or option B? The analyst risk-informs elements in the process by identifying vulnerabilities and using this information as a tool to inform decisions. The industry also uses PRA and HRA to support various risk-informed applications. They are used to estimate the change in risk caused by proposed technical specification changes, plant changes, etc. So called risk-monitors are being used to track the risk at the utilities at any given time caused by equipment status, which is then used as a planning tool and for risk-informed decision making. If a utility wants to change a particular element in its licensed design or operation they send the NRC a proposal, which will use risk as one of the supporting arguments. NRC has no legal requirements in this regard, but has endorsed this approach via Regulatory Guide 1.174.

The information gained from the HRA is used to define the safety basis for the utilities. Some utilities go further and use HRA to plan and manage daily activities. It's important to apply the risk insights gained from the PRA and HRA, and some of these insights might be suitable to be incorporated in day-to-day plant operations. For example, everyone at the plant should know where important risk equipment is, what the important risk initiators are, and everyone should know what their key operator actions are. The information gained from the HRA could also be used to inform briefs, e.g., pre-job briefs to make these briefs more accurate and useful than they are otherwise.

I) **Value Added by Using Human Reliability Analysis**

Some utilities have used HRA and PRA extensively in revising their operations, updating their plant, developing procedures for full-power operation, and developing procedures for low-power operations. HRA has identified important human actions, and the industry has put a great amount of attention to these actions and has improved the procedures, training etc. Over the years, HRA has provided a solid basis for understanding regarding what the utility is doing, what the crews are doing, and how the performance can be improved. Some utilities even use HRA to keep indicators of day-to-day changes in risk to support their risk-informed decisions regarding operations.

Even though there are some examples of the added value of conducting HRA analyses, the industry still must see the obvious returns on investments in order to be willing to spend the resources needed to conduct a quality HRA . One of the main challenges for the HRA community is to convince analysts and their managers why more detailed analyses are needed, and why the results from such analyses would be more reliable than results from less detailed analyses. The HRA community has not established very fundamental measures of economics or return on investment as has the human factors community. For example, a human factors expert can say: "if we do a usability test, this is how much money we can save". In HRA there is often no measure available of the value added. The value added by HRA could be measured in terms of money, lives saved, incidents prevented, etc. HRA identifies the weaknesses in a system, which can be frustrating to system designers and maintainers. Who wants to have people pointing out all your flaws? Therefore, it is important to have good examples of the value added by HRA to the organization. There is a lack of good examples of HRA activities that could be used to characterize the value and role of HRA. Unfortunately, there are more examples of poorly conducted HRAs than good ones. There might not be the amount of acceptance in the industry needed to actually apply the research findings with regards to HRA. This needs to change.

The PRA community needs to see the advantages of HRA, and they need to see the benefits of HRA tapping into the strengths of human factors. In other words, PRA needs to better understand and appreciate what HRA does in order to be able to champion it.

However, PRA analysts seem to appreciate the value the HRA team can bring to the process to a greater extent now than before. There is a realization that human failure/human errors are a significant contributor to the overall risk, and that it needs to be accounted for. The regulatory body also needs to see that HRA could be effective in preventing errors. The idea that the human is an important element in the complex system needs to be better promoted.

2) **Differences Between the American and the Nordic Industry**

Both the Nordic and the American nuclear industries and regulatory bodies agree that HRA is an integral part of the PRA, and that it is important to maintain this strong relationship. HRA identifies areas of weakness and areas of risk significance, where human performance contributes to risk. The HRA insights are used a bit differently in the different industries. The Nordic nuclear industry has a greater focus on the contribution to risk, while the American industry has a focus on both the contribution to risk and on how human performance needs to be improved in various different settings to reduce its contribution to risk.

In the American nuclear industry there is a difference between the methods the utilities use and the methods the NRC develops and uses. In the Nordic nuclear industry, there is one method (THERP) that is used almost exclusively for conducting HRAs. At the NRC, the Office of Nuclear Reactor Regulation uses SPAR-H for analyses conducted in the SDP and the Accident Sequence Precursor (ASP) programs, and the Office of Nuclear Regulatory Research develops new methods, such as ATHEANA [14]. The Nordic regulatory bodies do not develop any HRA methods. The American utilities use the EPRI HRA Calculator. The Nordic utilities use the THERP method, or an adaptation of this method, since the utilities know that the regulatory bodies will approve this method.

The Nordic nuclear industry has focused on plant upgrades and control room modernizations for many years. In the design process, PRA serves as a design validation tool, and therefore HRA is also used in the validation. Apart from the analyses in the plant's Safety Analysis Report, it is in the design validation that both PRA and HRA mainly are used in the Nordic nuclear industry. The American nuclear industry has not had as heavy a focus on upgrades and modernization as the Nordic nuclear industry. Therefore, the use of HRA in the validation process, and in the design process as a whole, is very limited, although the recently formed New Reactor Office at the NRC will be assuming some of this function. The American nuclear industry, as well as the Finnish part of the Nordic nuclear industry, is facing a related problem. They have a need to adapt the PRA and HRA to successfully analyze advanced systems and control rooms. The HRA community needs to place more emphasis on these aspects.

A main difference between the Nordic nuclear industry and the American one is that the American regulator maintains and uses PRA models to review licensee performance. The Nordic regulatory bodies rely on the utilities' PRA models. The American model demonstrates that maintaining PRA models for the purpose of reviewing performance is essential to risk-informed regulations. The use of risk-informed regulation in the American nuclear industry demands a good dialogue between the regulator and the utilities, especially if the result from the utilities' PRA model differs from the regulator's model. In the sense of interaction regarding HRA and PRA results, the Nordic regulatory bodies do not communicate with the utilities as extensively as in the USA due to the fact that HRA and PRA are not used as much in support of risk-informed decision-making in the Nordic nuclear industry.

C. Relationship Between Human Reliability and Human Factors

Dealing with how humans act and behave in complex systems and dealing with human-machine interfaces - that is human factors. Since HRA analyzes and identifies human errors in complex systems, there is clearly a relationship between human factors and human reliability. In order to conduct a credible and reliable HRA there needs to be support from human factors to obtain the correct understanding of human behavior in the context of a complex system, and how the performance of or output from the system affects human performance. The human factors community can also help identify which performance shaping factors are important in different situations.

The purpose of using HRA by the regulator and industry is not only to be compliant with regulations, but also to provide feedback to operations and system designers. The insights from predicting the human error probabilities and conducting the HRA should be used to improve human performance at the utilities. The relationship between human factors and HRA should therefore comprise a feedback loop. First the control room, the procedures, and the system that the operators work in should be designed using the best available human-system design principles. An HRA is then conducted to examine human reliability aspects, which are inputs to the model of overall risk at the plant. This information should then be fed back to the designers to provide insights on what can be done to further reduce the risk of human errors, and to make the consequences of human error less severe. A correctly conducted HRA should provide useful insights as to what would influence human behavior. This information should be fed back to influence the design of the control room, panel layouts, processes, and procedures.

Human factors is - at least at the NRC - the area that analyzes and documents the knowledge that feeds into the HRA. In other words, human factors looks at human actions, the plant state, and equipment performance. Human factors also looks at what the crew is supposed to do, the level of indications available to the operators, the quality of the procedures, how competent the crew is, etc. All of this is determined by analysis of human performance that is based in behavioral science. Human factors analysts as a part of the HRA and PRA team will therefore provide additional insights for operations that may impact both PRA and HRA inputs. There is also an important interaction between the PRA and HRA communities in terms of how the two analysis approaches can support each other when it comes to identifying the problems, the priorities, and what the human factors community is currently focusing its research on.

Qualitatively, the fields of HRA, safety culture, and human factors are not that different. HRA is a subset of human factors, for example. However, in speaking with traditional human factors practitioners, they do not always view it this way. A lot of the foundation for performance shaping factors and base failure rates was first developed in the human factors community. Another way to describe the relationship is that human factors and HRA are different but related disciplines. Human factors and HRA have different focuses and goals and might not always understand each other’s goals and terminology. HRA has always applied a rigor, which is a good anchor and balance for safety culture and human performance. The two different but related fields are not looking at different errors, but the intent of the analyses can be quite different. HRA and human factors have different needs when it comes to information. HRA is a bit more practical and more tool-oriented than human factors. The main difference between human factors and HRA is that human reliability focuses on very specific events - localized analysis. Human factors has a more global view. The strength of HRA compared to traditional human factors is that HRA offers a predictive ability, i.e., the HRA analyst tries to predict potential human errors that may occur. Such predictive analysis allows for barriers to be put in place to reduce the likelihood for these potential human errors to occur.

The human factors community can provide useful information to the HRA, and it can also really apply the findings of HRA. HRA can support human factors with understanding performance probabilistically. It must be recognized that human behavior is not deterministic, which one might perhaps argue is the case for engineered systems. There is a strong probabilistic component to human performance that must be recognized. Human factors can take information obtained by the HRA such as the risk significant areas and craft strategies for dealing with weaknesses. The HRA identifies where and what the problems or weaknesses are, but the organization needs human factors to know how to improve the weaknesses, in the sense of what kinds of guidelines are needed to improve. Human factors has guidelines for how to design to avoid errors - not to put things too close together, not be confusing, etc. Hence, the understanding of human performance is guided by human factors standards and guidelines that the regulatory body and the industry have developed over the years. However, human factors does not typically consider the range of drivers that HRA might consider, i.e., the performance shaping factors that are identified while conducting an HRA. To really improve the identified weaknesses one needs both the human factors guidelines and the identified performance drivers from the HRA.

Human factors is typically concerned with the design and operation of one kind of system or another. The range of systems is very broad - from pencils to human cognition. Human factors engineering provides the technical basis for performing HRAs, and for developing methods and data to quantify human reliability. The information gained in human performance and human factors work could certainly be used to improve HRA. It could, for example, be an input for how to predict human error probability. Some benefits from human factors in terms of modeling and simulation of performance could feed into the HRA. HRA should also draw more from the theory of human factors to better ground its methods.

Human factors and HRA have different views of failure space and error reduction. HRA lies in the failure space and tends to focus on the negative, while human factors focuses more on the positive, i.e., what can be done to make performance better? HRA is selectively focused on failures, emphasizing the knowledge of what can lead to failure. HRA is mostly applied to systems where human errors will have significant consequences, e.g., nuclear power plants, military systems, and space systems. Human factors does not always incorporate this scope into its analyses. Human factors is mostly focused on improving the design of components or products.

People who are strict experimentalists in human factors sometimes have a hard time adapting to the failure-oriented nature of HRA, i.e., the fact that HRA is constrained to fit into the PRA. The human factors community needs to understand that what the HRA community does might not constitute a fundamental discovery of human behavior, but an engineering tool to support a decision. HRA wants to make sure that the supported decision has some foundation and that the decision is as correct as it possibly can be. Human factors provides the technical foundation - the ultimate knowledge about human behavior and cognition. HRA needs to take what is known about human behavior in certain conditions and model it in a way such that it can be brought into the PRA. Engineers and human reliability analysts are often driven by urgency to do something for a PRA project - to produce numbers and identify human errors. Human factors analyses are usually not driven by this urgent need. If a human factors analyst is going to develop an HRA methodology for quantification, then they need to understand how, when, and where the results of the method are going to be applied to the PRA.

HRA and human factors have different views of quantification. Human factors is trying to minimize the likelihood for consequences of human activities, but does not have a detailed focus on the mechanisms of failure modes, the probability of their occurrence, and the different contexts in which errors might be more likely.

Human factors has been a bit skeptical of HRA in the past since HRA was not very empirically based and did not have adequate methods. In HRA, the analyst needs to estimate human error probabilities, which are generally not needed in human factors. HRA still does not have a valid empirical base and therefore human factors analysts are sometimes uncomfortable with the fact that human reliability analysts might have to come up with numbers that are not backed up by much science. Therefore, the quantitative part of HRA seems to be the least in synch with human factors. HRA is sometimes viewed as a math game rather than a field that really is going to improve safety.

There can and should be meaningful interactions between human factors and HRA for the qualitative aspects of the HRA - what to improve, identification of how to avoid or mitigate unsafe actions, and how to avoid undesirable consequences. The industry's work with human reliability and the improved interaction between the fields of human factors and human reliability have led to a reduced likelihood of human error. Even though the interface between human reliability and human factors has been improved, both historically and today, HRA has been conducted with little or no human factors support. This, despite NUREG-1792 - Good Practices for Implementing Human Reliability Analysis (HRA) [15], and its recommendations that human factors expertise should be included in the PRA team. A part of the problem is that analysts from the two fields have not necessarily tried to work together. There has traditionally been a greater focus on dismissing each other instead of trying to work together in a multidisciplinary team. In practice the different analysts do not take the time to interact and learn from each other in a meaningful way. However, HRA can be used as a way to bridge the differences between the engineers and the human factors analysts within a project. A multidisciplinary team is essential to conducting a good HRA. Therefore, the relationship between the engineers and HRA analysts - and between the human factors and the HRA analysts - must be improved.

There is a need to understand the cognitive demands in order to understand the interaction within operator roles, between roles, and interaction with computers. The HRA analyst must identify what will work effectively and what will not work effectively. Based on this, the analyst can analyze, understand, and predict aspects of human performance. These results can later be translated into a form that fits into the PRA framework. The parts of human factors that seem most relevant for HRA are the task analysis and the understanding of the cognitive situation the people are in, rather than the physical arrangement of things.

Researchers are trying to close the gap between HRA and human factors that have arisen over time. Historically, HRA went its own way - separate from human factors. Human factors developed a large number of applications, such as learning, designing, usability tests, and things like cognitive science, while HRA focused on risk assessment. For a while the HRA analysts forgot the human factors side of it, but it has slowly been integrated back into HRA. Nowadays when researchers are improving HRA they borrow ideas from human factors, e.g., when trying to characterize and quantify human performance, actions, and decisions. Today it seems as if experts really do want to close the gap between HRA and human factors. Techniques such as the Cognitive Reliability and Error Analysis Method (CREAM) and A Technique for Human Error Analysis (ATHEANA) [16, 14] try to focus on more recent theories of the analysis of human performance in complex systems. HRA has gone from being a superficial to a more detailed analysis, and this has helped strengthen the relationship between experimental work, data, and cognition models. This movement has improved the qualitative understanding of human errors. This has (and will) help operations and is a good input to help design.

D. Relationship Between Human Reliability and Probabilistic Risk Assessment

Probabilistic risk assessment (PRA) started as a hardware and process model to which HRA was added at a later stage, mainly as an afterthought. HRA is still sometimes viewed as an add-on to the PRA. In the beginning, PRA and HRA were quite divorced in the process of constructing the risk model. The HRA people did not have enough understanding of the technical system or scenarios they were analyzing. To improve this relationship, PRA analysts started getting involved in the HRA process to support the HRA analyst with valuable knowledge about the system.

In the past PRA was used to identify vulnerabilities and not so much for risk-informed applications, i.e., to use a number to justify an application. The analyst mainly wanted a ranking of risk contributors and was not so concerned about the value of the specific human error probability. Today the number is more important, and we need to back it up with knowledge from both the human performance side and the PRA side. The relationship between PRA and HRA has improved over the years. PRA used to come to HRA to get a number, but today it seems more like the PRA community is as interested in the qualitative insights as in the HRA’s quantitative estimations.

PRA treated HRA as a component with failure modes the same way PRA treats hardware. Today, static PRA still treats human error as one single event, which potentially reduces the importance of human error. Many utilities' models treat all human actions as one human failure event in the fault tree, which may miss important issues due to the minimized scope of the human errors. Humans are more important than is reflected in how they are treated in current PRA models. The PRA community is starting to work more with dynamic models in which all the relevant events in the HRA might be modeled. For most applications of HRA, the HRA is driven by formalism or tractability constraints of how to fit the information into the static PRA. HRA needs to model human behavior in a way that fits into the PRA. Therefore, the HRA methodology forces the analyst to look at humans as logic structures that are comparable with engineering methods and techniques, e.g., fault trees and event trees. The way the static PRA models are set up makes it difficult to model the actual factors that influence human performance.

The strength of HRA lies in identifying where operator actions are important and which actions these may be, i.e., HRA provides insights about human performance that are needed to gain a more complete risk picture. Some argue that the primary goal of HRA is to provide human error probabilities for the PRA, and if the analysis provides some useful insights for operations, it is a bonus. HRA identifies the human failure events that should be modeled in the PRA and provides the support to predict the error probabilities for these human failure events. Either way, there is a circular relationship or feedback-loop between the PRA and HRA. PRA provides input to the HRA in the sense of scenarios and context to be analyzed. The HRA provides the human failure events and the human error probabilities for the PRA.

In the classical PRA approach the HRA and human factors analysts worked in isolation from the rest of the PRA team, which created a lot of legacy issues. Today, there is an awareness of the need for a multidisciplinary approach. It is hard to find all relevant knowledge in one person. There also needs to be an understanding that the engineers might not always have enough human factors knowledge to conduct an HRA, and that HRA analysts might not always have access to PRA and system knowledge. Traditionally, the HRA is mainly conducted by PRA analysts – either at the utility or by contractors - who might have some experience doing HRA. They might even have some understanding of human factors issues that they have picked up on the job or through training, but they are not human factors experts. In order to improve the relationship between PRA and HRA, people from both fields need to work more closely together in modeling the system. Everyone should understand the underlying concepts of PRA. HRA needs to understand PRA, and PRA needs to understand HRA. Letting human factors/human reliability analysts conduct an HRA without enough training, they probably will not appreciate the fact that PRA is its own discipline and has very specific requirements. If PRA analysts without adequate human factors training conduct an HRA, they may conclude that the human events do not contribution significantly to risk since engineers tend to look at human factors as being soft, made up, and mainly based on common sense. It is the HRA analyst's role to understand the procedures, the plant alignments, and to identify functional successes and failures based on the PRA application. A correctly conducted HRA involves operators and trainers, and looks at what models the plant is relying on. Walkthroughs should be conducted to identify how the operators carry out their roles and what relevant training is involved in the scenarios.

The utilities and the regulator are trying to come up with the best picture of risk that they can given current available information. Human behavior must be modeled in some fashion to ensure that a significant part of the risk picture is not missing. Therefore it is important to conduct the HRA. The results from these analyses are very useful. A good HRA based on good data, a good methodology, and competent analysts applying it can make the PRA more realistic. To achieve PRA results that are technically sound there is a need for a technically sound HRA. Therefore the quality of HRA plays a very important role in the quality of the PRA. HRA methodology needs to be improved to the point where it can provide useful qualitative insights and more reliable, more accurate, more extensible numbers to the PRA. This will help HRA be viewed as a contribution to the field rather than something PRA just has to accommodate.

An idealistic view of the relationship between HRA and PRA is that HRA is an integral part of PRA and the two work together to analyze the complex system. PRA is supposed to model all hardware, software, processes, external events, human events, and organizational factors. HRA is integrated along with data and logical models for system functions and success criteria. An overall integration of these inputs into the PRA model yields a risk profile for the plant and the ability to compare the various contributions to plant risk. A PRA is a model of how a plant will or will not respond to a particular initiating event, and in principle this would include every phenomenon that is important to that response. Human actions are clearly important components of the plant's response. HRA provides a way to incorporate human behavior into the PRA models.

HRA can be viewed as a key component to a PRA, and the HRA topic is not diminished by referring to it in these terms. The end goal is not to perform an HRA for its own sake, but to incorporate the HRA results and insights into the PRA in the best manner possible. Often HRA and PRA are described as if they were completely different disciplines. This is not true. One does not have to have PRA to conduct an HRA, but in practice – at least in the nuclear industry - they are very tightly connected. HRA is almost exclusively used to support PRA. By separating PRA and HRA, they might end up further away from where they can make an impact. This could potentially make the analyses less significant when it, in fact, needs to go the other direction.

The HRA portion of the PRA might not always receive a lot of focus. There is a notion that a PRA is conducted and then some human error probabilities are added. This mindset needs to change. HRA needs to be reintegrated into the PRA, and the final result of the PRA should come from a multidisciplinary team instead of the PRA expert. In practice - outside the research world - the frustrating relationship between PRA and HRA remains. The HRA analysts are called in to quantify specific values out of context, even to the point where PRA analysts provide an overly narrowly defined human failure event, leaving only quantification by the HRA expert.

Traditionally, there is an institutionalized interaction between PRA and HRA which, unfortunately, diminishes the importance of the human actions. As long as HRA is treated as a subset of PRA instead of as an equal partner, HRA does not have the ability to make the necessary contributions. As discussed earlier, the human contribution to risk is at least 50% [17], which indicates that the assessment of this contribution is important to understand and reduce risk. The concept of dynamic PRA is one solution to this because it treats the human and the system as equally important.

Quantifying human error is very context dependent. The PRA is one area that provides the context for human error. Therefore, HRA needs the PRA to provide the context in order to estimate credible human error probabilities. Quantifying human error probabilities outside of more integrated risk assessments could also be problematic in communicating what those results really mean. Therefore, HRA must remain closely related to the PRA.

E. The Future of Human Reliability Analysis

HRA budgets are still small compared to PRA, and yet it's noted that HRA is a very large driver in the risk assessment. HRA has always been the weak sibling to PRA in the sense that it gets a very small portion of the budget and is under pressure to produce a certain kind of answer that only follows a certain form, and to do so relatively quickly. This leads to a dearth of resources. To conduct HRA correctly, the industry has to spend more resources than it has been willing to do. A lot of money has been spent addressing hardware reliability, and this has increased the credibility of this portion of the risk assessment. Money now needs to be spent on human reliability to improve this part as well. According to Trager [17] human error is the source of 50% to 70% of the problems in nuclear power plants, and there are even higher estimates to be found in other research literature. Assuming that the human contribution to risk is 50%, it is daunting that the portion of the risk assessment budget that is spent on the human contribution is much less than 50%. The given percentage of the total PRA budget that is spent on HRA differs among the interviewees but ranges between 0.1% and 20%. Regardless of which estimate is the closest match to reality, it is interesting to note that there is a discrepancy between the human contribution to risk according to human factors research and the percentage of the budget that goes into this area.

The right amount of investment allows the HRA team to make reasonable assessments and projections of what potentially might happen. The resource demand is a problem for HRA because conducting an HRA according to the Good Practices for Implementing Human Reliability Analysis (HRA) [15] is very resource-intensive and the organization rarely puts in enough resources. The organization might not have the personnel, funding, or time required. Sometimes shortcuts are taken. These shortcuts often put too much focus on the bottom-line numbers the analysis produces. There is not much room for qualitative insights. Better funding of HRA is essential - the knowledge of safety in human-operated systems cannot be increased by excluding humans from the studies. Therefore, the organization must be willing to put in the recourses needed to conduct the

HRA analysis the right way. The nuclear industry's safety awareness is growing; as it matures into new areas and gets beyond control room operation, HRA needs to grow as well and thus needs to be funded accordingly.

There are a lot of human reliability analyses performed inappropriately due to the HRA or human factors analysts' lack of understanding of what really is going on at the plant, and due to the PRA experts' lack of understanding of how a human could react in a specific situation. In order to improve the quality of HRA – and hence the quality of PRA – the level of understanding and knowledge of the analysts must be increased. It is essential to increase the knowledge level of all the participants in the PRA. Most of the HRA practitioners have a strong PRA and engineering background but not so strong a background in human factors or psychology. Many engineers do not understand why they have to be trained in human factors in order to conduct the analyses. There is a common belief that in most cases all can be done through common sense. Evidence shows over and over again that this is not the case. The design of old control rooms is an example of common sense applied without much human factors knowledge. The less than adequate understanding of human factors is also true for some parts of the community that are trying to reform HRA. The main reason for this is that HRA practitioners in general tend to be PRA practitioners, i.e., engineers. Some of them have worked in HRA for a long time and therefore have gotten involved in HRA research. Having engineering in the HRA community is of course not bad at all, but there is a need to become more sensitive to human factors issues.

Even though HRA can be viewed as an engineering tool, it is important to remember that HRA actually is a scientific endeavor and it has a whole community of researchers behind it. In HRA research, people are really trying to incorporate cognitive issues to think about performance shaping factors that are likely to impact errors of intention as opposed to errors of execution. HRA as a field is also somewhat narrow. Even so, HRA is a more rigorous discipline (in the sense of having a clearly defined and standardized process) than safety culture and human performance and can sometimes be viewed as one generation ahead of safety culture and human performance. But some of the main issues in safety culture and human performance have not yet been incorporated into HRA. Joint projects among researchers, the regulatory body, and industry are important in order to gain acceptance for new HRA developments. The industry needs to be involved in order to feel ownership of the results.

In the US there is a shortage of HRA expertise and most of the current HRA experts are nearing retirement age. Another big challenge for the HRA community is that some of the brightest minds in the field - young minds especially - are not sticking around when they realize that the PRA and HRA fields are quite retrograde, with no real desire to change or update. The PRA community is hesitant to change because it is heavily entrenched in the static logic models that have been around since WASH-1400 [18]. These two factors combined point out a weakness in the HRA community that is essential to address and resolve in the near future. If no HRA analyst will fill the void, the HRA community risks being diminished when the current experts are retiring. There is also a fear of introducing regulatory uncertainties to the process by introducing models that are not yet well-known to the regulator or to industry, which influences the willingness to adopt new HRA research findings. Traditionally, the industry felt as if their needs and input were ignored and that the researchers just did what they wanted to do.

1) **Methodology Development**

HRA has some technical shortcomings, which need to be addressed in the long-term if HRA is to be credible and usable for PRA. The older HRA methods used by the utilities and regulator do not have a complete scope, e.g., they don't all address pre-initiating events - a human action that leads to an event. The quest for perfection in HRA sometimes becomes its worst enemy. It is easy to get sidetracked trying to make things perfect rather than making them reasonable. Even though it is essential to understand the underlying human performance models, the main purpose of HRA is still to inform the PRA of the human contribution to risk. People are becoming more aware of and better understand the limitations of HRA because we are pushing the envelope with PRA. HRA has matured in a way such that even current methods can provide results that address operational problems in a meaningful way. To obtain these results, the HRA must be conducted the right way, i.e., in accordance with the *Good Practices for Implementing Human Reliability Analysis (HRA)* [15].

Another large challenge for PRA and HRA is to break away from the way things have been conducted in the past, e.g., static fault trees and event tree models. One direction for this change could be toward simulation-type dynamic models. The challenge is to make the change without overwhelming the regulatory system with a lot of uncertainties. Software reliability and the reliability of controls could be degrading the human reliability. These things are better modeled with dynamic models than they are with static fault trees and event trees. HRA could benefit from the mathematical approaches that recently have been developed in PRA, such as Bayesian and dynamic approaches. This technology could be brought over to HRA.

Human factors becomes even more important when analyzing scenarios where the operators are supposed to handle conditions that they rarely - if ever - train on or experience in reality, such as fire, earthquakes, and post-core damage environments. Today, HRA methods for at-power operations are applied to these other applications. It is essential to question whether the underlying assumptions and methodology for at power operations are valid for these applications. There is an increased awareness of the need to cover human actions in these newer applications, but there is not necessarily increased funding to support that. There is a need for a domain and application specific set of HRA tools that everyone understands and uses.

HRA has a role in the PRAs for new designs for the advanced reactors. For the new reactor designs it is going to become more important to quantify the risk profiles early in the design stage. This enables changes to be made to the design that improve safety, but requiring less effort and resources. It is much cheaper for the utility to pursue a change in an early stage in the design process rather than having to fight the battle when the plant design is finalized and the plant is either under construction or already built. This is especially important for designs where there are no existing operational experience data to rely on. It will be a challenge for the HRA community to generalize the HRA methodology so it becomes useful for new reactor designs where there exist no empirical human performance data. There is a need to understand the differences between the new and old reactor and control room designs , and what affect these differences will have on human performance, within the scope and context of the PRA and HRA. The factors that influence human performance might be different in the new designs. If so, these factors must be identified and their impact on human performance estimated. It will be challenging for HRA to characterize crews working in the presence of advanced systems and to estimate failure rates with regards to different levels of staffing and different concepts of operation.

"We are trying to hook up a typewriter to the Internet" – Anonymous interviewee

Current HRA methods and tools used by the utilities are old and need to be updated, but there is an emphasis on a one-size-fits-all approach to HRA. The HRA methods were not designed for these new applications. Instead of using old technology, new HRA methods tailored to specific applications should be developed. The assumption is that these tailored HRA methods would be more successful in predicting and quantifying errors because they would be more focused on the application at hand, instead of being a generic method. Old methods like THERP might not identify all the factors that really influence accidents in advanced plants.

There is a need to find a balance between very sophisticated HRA modeling techniques and the need for something that somebody can just pick up and use to obtain a quick estimate of error likelihood or a quick identification of an error source or error cause. Therefore, it is important not to introduce too much complexity in the tailored methods. There is a risk that the industry will not adopt more rigorous and application-specific methods to replace the ones used today. The level of complexity of the HRA method with which people feel comfortable is not assured to be a level that gives them credible results. However, the HRA community does not currently have enough evidence to back this up.

Similar to the importance of having a tailored HRA method, it is important that the method be scalable to suit the application at hand. It might not always be feasible for the analyst to conduct a very detailed HRA and a brief screening analysis might not be sufficient – the two main types of HRA methods. Therefore, other alternatives such as scoping approaches are needed. The scoping approach lies between screening and detailed HRA.

It should be emphasized that the success of a scalable HRA method lies in the ability to match the scope with the purpose. An analysis of a small set of actions might not find it relevant to analyze outages or severe accidents, which could be of great importance to other applications. If HRA is to be used in the design process or outside the PRA, it is necessary to have methods that possess the scope needed for the analysis at hand, both with regards to level of detail and in the focus of the analysis. HRA provides an understanding of the areas of potential errors. This knowledge about potential risk significant consequences is important to the utility. This knowledge or understanding is not only important when managing risk, but also when making investment decisions. The HRA also provides the utilities a structured methodology for dealing with identified concerns. Therefore, it is of great importance that the information provided by the analyses is as close a match to reality as possible. One could argue that there are already enough HRA methods out there today. It is true that there are dozens of extant HRA methods, but most of them are older methods. It is essential that the HRA methodology used be appropriate for the application analyzed. It is also utterly important that digital I&C, advanced technology, and automation be appropriately handled by the HRA. Most of the methods in use today were developed in an era of analog control room systems .

HRA can be used to identify weaknesses in the human-system interface. This makes HRA a powerful tool, but it is essential that the HRA methodology be sensitive to the different factors that influence the interaction between the operator and the system. It is crucial that the HRA methods adequately address digital instrumentation and control, advanced displays, and increased opportunity for automation. Most of the HRA methods that have been around for a long time do not address these issues in a sufficient manner since these advanced technologies did not exist in the control rooms by the time the methods were developed. Many of the newer HRA methods that have been developed are based on data from the older methods and therefore risk not addressing the human-machine issues in a satisfactory manner. Therefore, it will be necessary to develop new HRA methods and tools that are more attuned to today's advanced technology.

As discussed earlier, there is a strong relationship between the fields of human reliability and human factors as well as a strong relationship between the fields of human reliability and PRA. HRA can serve as a bridge between the human factors community and PRA, i.e., the psychological and engineering work at the plant. The qualitative insights from HRA can be used to both inform the human factors work and the engineering work, e.g., it can be used to improve procedures, operator training, and the control room interface design. The usage of the qualitative insights from the HRA will become even more important when using HRA in the design process. Even though the quantitative data from the HRA are needed by the PRA model, the qualitative insights can inform the system designers' decisions. There is a movement within the HRA community to develop methods that have a stronger qualitative focus than some of the most commonly used methods, e.g., THERP and SPAR-H. ATHEANA [2, 13, and 14] is one example of a newer HRA method that emphasizes the qualitative part of the HRA.

The American nuclear industry wants methods that are easy to apply in the field and that have understandable data. They do not want a lot of theoretical arguments and bases, because these do not tell them how to apply the models. Therefore, researchers need to focus on developing usable PRA and HRA models - not only theoretical models. When SPAR-H and ATHEANA [13, 14] were developed there was a disconnect between the practitioners' needs and the view of researchers in the HRA community of how to conduct a proper HRA. SPAR-H tried to address the practical need the NRC had, which was to do risk assessments in the accident precursor program and to look at events from the perspective of the enforcement process. The NRC needed a straightforward method that the inspectors could use to estimate human error probabilities. SPAR-H has been successful in the sense that there is more of a consistency in the human error probabilities provided to the inspectors. However, the HRA community sometimes views SPAR-H as a simplistic and easy-to-use method that does not place enough emphasis on the qualitative part of the analysis. ATHEANA on the other hand, has a strong emphasis on qualitative insights, but the industry often views ATHEANA as being too resource intensive and therefore has chosen not to apply it. This shows that it is important to have a close interaction between the researchers and the practitioners when developing HRA methods.

The question of how many HRA methods really are needed remains unanswered. There might not even be a clear answer to the question. Many different methods have been developed, and over time confusion arose regarding which method was the most correct one. This is a weakness the HRA community is currently addressing. The number of methods to choose from makes people fall back on what is familiar, such as THERP and SPAR-H [2, 13]. In terms of day-to-day practice, people tend to fall back on these methods, since they get the message across and are somewhat easy to use. Today, there are too many competing HRA methods and this makes it difficult for non-practitioners to understand why they would use one method over another. Having too many methods may also limit the credibility of the HRA technology. In HRA there is a constant quest to understand which method to use when. Neither the regulator nor industry has developed selection criteria for which type of HRA method to use for which question. Some of the methods are more suitable for certain types of problems than others. Sometimes the difference in method used can lead the plant and regulator to end up in a disagreement. Increasingly, both are trying to use the same approaches since that makes the discussion easier for both parties. It is easier if everyone speaks the same language.

One of the largest drivers for risk is human performance and how operators respond in certain situations. Therefore, these things should be modeled by the HRA. Particularly, it is important to look at errors of commission, i.e., well intentioned but inappropriate actions the operator could take. Current HRA methods are still very driven by errors of omission and do not handle commission errors in typical applications. Three-Mile-Island-style omission events, where minor hardware failure led to a series of human events that led to core damage, are rarely modeled. There is a need for a broader scope for HRA and not only looking at errors of omission. There is a need to look at all types of events, especially in the era of new reactor designs, which consist of passive systems where cognition errors and commission errors could be dominant.

There is no consistency in how the HRA is being used and it has a certain grayness and sensitivity to it. There is no good knowledge regarding how reliable the HRA methods are themselves. There is no good way to deal with the variability in HRA, which is inherent in the HRA process itself. One example is the task analysis where there are various ways to decompose the task yet a lack of consensus on how to decompose, what level to go to, and when to cut it off. A lot of effort needs to be put into guidance for how to decompose a scenario. This would reduce the analyst-to-analyst variability, as well as some of the method-to-method variability that exist in HRA today. Uncertainty due to the inconsistency between methods needs to be reduced. For example, different HRA methods assess human error probabilities over a wide range of values, but these values are not always consistent across methods. One way to reduce the variability between method predictions is to have better validated data. Human error probability prediction across the methods is not totally independent. Most HRA methods use the human error probability estimates in THERP. Even though new HRA methods are being developed, the estimates in THERP have not changed, i.e., old estimates are being used and repurposed. New data and better method guidance are probably key to reducing the variability across methods.

There is a great need to get more consistency in the HRA results. Today there is too much analyst-to-analyst variability. Flexibility or lack of specificity in methods leads to analyst-to-analyst variability. HRA can be very driven by the analyst rather than by the HRA method. The HRA community is currently trying to eliminate as much subjectivity as possible in order to make the results more objective. The variability can be reduced in practice, but there is no assurance if that will lead to better results or not. Traditionally, method developers have not provided enough guidance for how to apply the methods. The analyst-to-analyst variability will be reduced by better guidance. However, it will be a challenge to develop guidance to make HRA results more accurate and consistent. Lack of consistency in results equals poor accuracy. There is a need for better accuracy.

Most HRA analysts are quite comfortable with tools that are not fully validated due to the lack of scientific basis for the assumptions. Therefore, there is a risk that too much credibility is given to the bottom-line numbers. People are going to demand more credible methods as a sounder foundation for technical decisions. HRA methods need to incorporate new data and new modeling techniques to increase the scientific basis of HRA. There is also a need for a domain and application specific set of HRA tools that all practitioners understand and use. Hence, HRA tools must be developed to support the different applications.

Developing and improving models of human performance is a challenge to HRA. These can get to be very computationally complex representations and can be correspondingly quite resource intensive, e.g., for modeling the interaction between the operators and the plant, decision making, situational assessment, or execution of actions leading to different types of behavior and different cues to operators. Lack of understanding of human behavior and how to represent it are weaknesses of HRA that need to be addressed. To improve HRA we need to look to the human factors community since HRA does not use psychological models and does not have a sound basis. The HRA community has a lot to learn about human performance modeling.

2) **Human Reliability Analysis Data Collection**

HRA is usually viewed as quite subjective compared to the PRA. This is mainly due to the fact that there are operational experience data for equipment. The lack of data or evidence to back up the human error probabilities used in HRA is the most commonly mentioned weakness in HRA. The data in HRA are sparse and incomplete. The bottom-line is that the industry wants a grade or a number of the risk associated with some plant change. There are however, different opinions on how the data and numbers in HRA should be interpreted. In the big picture the numbers might not be that important. Both PRA and HRA analysts think in orders of magnitudes. They are not pretending that the detailed value is correct. It is the relative values that matter. This ranking of important aspects should be the main focus of HRA. HRA provides an ordinal type of ranking for the most important things to focus on.

In HRA, it is generally very unlikely scenarios that are being analyzed. There is not enough data to do an entirely empirically analysis, which makes it possible to question the validity of the analysis. PRA needs to realize that HRA is not mature. The fact that HRAs are able to generate numbers is not an indication that those numbers have a solid foundation. The HRA methods are designed to generate numbers, but that does not mean that those numbers should be trusted. Using the insights gained from the HRA to reduce risk is a productive way to use the numbers produced by the HRA.

PRA is supposed to help the decision maker with a particular problem. The numbers are valuable when supporting the analyst or decision maker to identify what is the most important risk to address; hence in a risk-informed process the risk values are important. However, the reason for performing a PRA is not to demonstrate an absolute level of risk unless the question demands that kind of answer.

Since the detailed values cannot be trusted, it is important to shift focus and identify the real factors that influence performance and the risk of human error. Today, the nuclear industry has a better understanding of the way performance shaping factors affect performance, but there is still room for improvement. These efforts can be focused on design and policy to reduce the probability of errors when the industry starts to think about the relative probabilities under different conditions. Policies regarding what technologies to allow and which not to, and how they should be implemented can be intelligently selected based on the information gained from the HRA.

Bayesian analysis can be used to solve some of the problems with the lack of evidence, especially if it is agreed that the numbers do not reflect real frequencies. The Bayesian methodology is really to use evidence or information in a general sense to estimate a quantity. There is no need to look for data in the traditional sense, i.e., no need for 1000 operators to get a failure rate. Some interviewees in this study argue that there will never be a comprehensive set of numbers that will qualify as good data if Bayesian methods are not used. Targeted analysis can be conducted to estimate a few reference points based on data, partial evidence, and quantitative/qualitative information. This would put the HRA community in a much better position to establish some credibility in the numbers.

Data needs to be collected in a controlled fashion so that it can be used in analyses when estimating failures and failure data. There is a need for well-defined failure modes and failure mechanisms. When this is in place, data can be collected and failure rates can be estimated independent of the industry to which the approach is applied. In this way HRA in the nuclear industry can start to use data from other industries as well.

Today the HRA community has access to a lot of data, but there is no good way to collect it. How do you transform observed data into information you would use in a quantitative framework? When dealing with humans you are not dealing with the same person, not the same type, not the same history, etc. Training might be similar but everyone interprets training differently. All of this combined, makes it hard to have good data. The HRA community tries its best to assign failure probabilities to human actions. In terms of PRA this assignment of probabilities is the same for systems and for humans, but in terms of how to analyze it, it's very different. There is a split in the HRA community when it comes to what data could be collected and how this should be done. Some think that there need to be similarly trained groups, under similar conditions, doing different scenarios which will be timed. This group of researchers argues that data valid for one plant is not valid for another plant due to differences in procedures etc. Other researchers believe that the data can be valid even if the conditions are not similar. Some others think that human performance models are the path forward.

Anyone who wants a real and reliable number to put in their model does not want to use HRA because it is really hard to get this from HRA. To some analysts who do PRA, HRA can be really frustrating in the sense that humans are very unpredictable. Humans can fail to do what seems to be a simple task, or they can succeed in the most unpredictable and creative ways.

The common belief however, is that all HRA methods today suffer from a lack of actual empirical failure data that can be directly applied to the scenario being modeled. The numbers used are not based on much besides expert estimations. There are still a lot of people who think HRA is a mysterious and magical process whereby numbers are pulled out of the air and that there is no concrete evidence to back up the numbers. Hence, the confidence in HRA results is limited due to the lack of empirical data. The HRA data sources are very scarce and hard to validate, therefore affirmative evidence for HRA is greatly needed. There is a concern that the data underlying HRA has not been validated enough. Empirical data could help to assess the numbers used and to ensure that the numbers are credible enough. The range of numbers used today is probably good or reasonable for the large numbers of events that are quantified in the analyses. However, these numbers need to be backed up by empirical data. The HRA community might end up with the same numbers, but by then the numbers can be supported by evidence.

HRA is mainly lacking data for areas such as low power and shutdown, fire, level 2, severe accidents, automated control rooms, new reactors, and digital I&C. Many of these issues cannot be addressed very well in a simulator and there is not much operational data collected. HRA analysts are used to settling for a ballpark number, but this will not be good enough when the industry is becoming more dependent on HRA. There is a need for data to support the next generation of reactors and to strengthen the risk assessments. PRA itself does not have much data for these advanced systems. The industry’s incentive to collect data would be to get new reactor designs approved. They need to be able to prove that people can perform within the new design, e.g., computerized procedures or highly digital control rooms need to be proven as good design. HRA and its data should be adapted to become useful in this process.

There is a lack of understanding of the ability to collect meaningful human factors data and information from actual operations. It is really hard to quantify human performance because humans can be so unpredictable, but the HRA analyst needs to make the prediction in order to get the failure rate. However, humans are hard to predict and have a lot of uncertainties to them. Even if the same person conducts the same task, it might be carried out differently each time. Sometimes there is too much emphasis on the number and not enough on understanding the human context. Therefore, some of the data collected in human factors could be used to enrich the HRA. Human performance modeling might also allow us to some extent to get around the problem of data collection.

3) **Human Reliability Analysis in Design**

HRA is used in risk-informed decision making, which should be extended to establishing operator performance thresholds. The goal is to model deficits and their effects on system safety. Such limits, or thresholds, are used in the verification of system design. However, they should be introduced much earlier in the design phase. There are different areas where HRA can provide guidance to the design process. HRA can be used very early in the design phase, e.g., if you have two competing designs - HRA can help analyze which one has the greater potential for errors, it can continuously analyze the system design to identify potential weaknesses, and it can be used as a verification tool.

HRA verification considers performance to be a function of hardware and human actions. In the Nordic Point of View study it was concluded that a system may have automated correction, preventing operators from learning from their errors [6]. When transferred to a different context, this could have consequences on plant safety. For design applications, HRA should be used to identify possible operator errors. In cases where high consequence errors are identified, HRA should provide design guidance to minimize their occurrence.

As discussed earlier, HRA can be used to identify weaknesses in the human-system interfaces, a benefit of HRA that should be utilized in the design process. By conducting an HRA early in the design phase rather than only using HRA as a verification tool, the insights gained from the HRA may be used to influence the design. The feedback loop between HRA and human factors becomes particularly important in the design process. The insights from predicting the human error probabilities and conducting the HRA should be fed back to the system designers to provide insights on what can be done to further reduce the risk of human errors and make the consequences of human error less severe. This use of HRA in the design process will become increasingly important due to the new reactor designs that are currently being planned. HRA will be needed to quantify the conceptual designs' risk profiles, and the qualitative insights from the analysis will help inform the system designers about potential human error scenarios that should be reduced to decrease the likelihood of human error. HRA can identify a large number of risks in the proposed designs and operations. These identified risks need to be prioritized to prevent errors later on. Hence, HRA in the design process can provide information regarding where to focus design efforts to make sure errors are not made, and on how to reduce the consequences of potential errors that do occur.

The predictive ability of HRA should be harnessed early in the design process to identify errors and find out which ones to address in order to minimize the risk of human error. There is not really yet a structured way in which to use HRA in the context of design; therefore, there is an urgent need to come up with a more explicit and structured way to use HRA concepts in design since there are many new reactors being planned around the world.

4) **Human Reliability Analysis Outside Probabilistic Risk Assessment**

Today HRA techniques, or even the philosophy of HRA, are not used in roles other than PRA support. This could be viewed as a barrier for the use of HRA. There is room for HRA to expand into other areas outside the control room and even outside the PRA, e.g., spent fuel and qualitative analyses of past events to understand why they happened. If a system is to be improved, and it is concluded that the driver for poor performance is the human, then an HRA that focuses on the human interactions within that system can be conducted without the need to consider the hardware reliability aspect of the system. However, if HRA is to be used outside the PRA there needs to be a greater focus on the qualitative aspects than the quantitative. There is much to gain from understanding what potentially can happen, where the risks are, and why having a poor organizational culture is a risk.

Lessons learned from applying HRA outside PRA can provide useful insights on how to improve human performance in the organization or situation. Conducting an HRA outside the PRA can also provide valuable insights on system reliability improvements.

5) **Human Reliability Analysis Outside Nuclear**

The key to the future of HRA as a field is to advance in other areas except nuclear, e.g., the oil industry, chemical industry, medicine, and aviation. Anything that can be done to strengthen diverse HRA fields ultimately serves as a benefit to its traditional applications in the nuclear domain. Expanding the domains where HRA is used probably means selling the HRA concept to the human factors community and showing them the value of borrowing ideas from other areas. Human error analysis is already being used more and more outside nuclear, e.g., in the medical and transportation industries. There is an interest in the medical industry in using HRA to decide what technology to install or in trying to quantify the effects of barriers provided by different policies or different procedures. These industries usually do not conduct PRAs; they use standalone HRA. NASA also uses HRA for some of their analyses.

Generally, every industry that has humans working in a safety critical capacity is a good place for HRA. Outside the nuclear field, HRA could be used as a part of human factors or for devising design solutions for all kinds of products. Other industries usually are not so concerned about the numbers (human error probabilities) as much as the taxonomy - error modes, failure modes, and failure mechanisms. The taxonomy is useful in informing organizations about their risks.

F. Communication

There are many misconceptions about what HRA is. HRA is perceived as a soft science and thus might not get as much respect as it should. It is important to get the word out there so that people understand what HRA actually is. There is a difference in language between equipment performance and human performance, and there exists a language difference between HRA and human factors as well. For example, the word “model” may mean different things in different fields. Increasing the understanding and diminishing the language differences, by developing a common well-defined terminology are important for reducing the barriers between the fields. There is not much dialogue between human factors and HRA. This needs to be changed. It might be as simple as working in multidisciplinary teams when conducting HRAs.

Sometimes human factors analysts have a difficult time communicating their needs to the rest of the organization. Their findings and insights need to be communicated to the engineers in a way that the engineers can understand so they can apply the results. HRA can help bridge this communication gap because it has a language that can be understood by both the human factors and the engineering communities.

HRA analysts and researchers must be more active in their interaction both outside and within the HRA community. There is a lack of communication between HRA practitioners and HRA researchers. Today it is almost as if they are two different communities. One of the reasons for this divide could be that the HRA practitioners may come from more traditional engineering and operation backgrounds. HRA researchers tend to come from human factors or risk/reliability engineering backgrounds.

The HRA community needs to be more open and communicative with others. This would help others to appreciate what HRA has to offer. HRA people especially need to advocate HRA to the human factors community to help them understand what HRA is and why it has its place. It is easy for HRA experts to talk in a way that no other groups will understand. Therefore, it is important that the HRA language – terms and jargon - is transferred into something that can be understood by non-human performance people or non-human factors people.

The issue of communication exists not only between HRA and human factors – communication between PRA and HRA must also be improved. HRA needs PRA analysts to be its advocates, but in order for this to happen, PRA analysts must understand the benefits of HRA. The dialogue between the human reliability analysts, engineers, and the operators is also very important. It is as important as any numerical result from the HRA. This dialogue will be a good indication of where human errors might occur, what barriers can be put in place to prevent the errors from occurring, and how to recover from errors quickly if they do occur.

IV. Principles for Human Reliability Analysis

The findings from the American Point of View study, which are discussed above, in conjunction with the findings from the Nordic Point of View study, serve as the basis for the ten principles presented in this section. The principles should be viewed as guidance for improving the HRA field.

A. Early Implementation in the Design Phase

There are different ways HRA can be implemented to support the design process. At a very early stage HRA can be used to compare competing design proposals. Thereafter, HRA can be used to evaluate human-system interface design throughout the whole design project. By using HRA analyses, risk significant areas or areas of weakness can be identified at an early stage so that the cost for changing the design is much less than if the risk were identified later during the verification phase.

There should be a focus on the feedback loop between the system designers and the human reliability analysts during the design process. The insights from the HRA should inform the work of the system designers in order to reduce the risk of operator errors occurring later. The insights from HRA should also be used to find ways to reduce the consequences of potential errors that might occur, i.e., reduce the consequence of errors that cannot be prevented by design. The system designers must inform the HRA analyst of the changes made to the design in order for the HRA analyst to conduct a valid analysis.

B. Tailored Human Reliability Analysis Methods

The HRA methods that are most commonly used are older and need to be updated. For the most part, they do not cover all the aspects that are in the scope of HRA today, e.g., advanced system design, digital control rooms, and applications such as fire and the post-core damage phase of reactor accidents. Since HRA is being used for more and more different applications, it is essential that the methods be adapted for the application at hand. For example, a method that is suitable for fire analysis might not be the most suitable method for evaluating human-system interaction aspects.

C. Scalable Human Reliability Analysis Methods

Not only is it important to have an HRA method that is tailored to the application, it is also important that it is scalable. It might not always be feasible for the analyst to conduct a very detailed HRA and a brief screening analysis might not be adequate . There is a need for something in between these two main types of HRA methods, e.g., a scoping approach. The success of a scalable HRA method lies in its ability to match the scope with the purpose of the HRA. An analysis of a small set of actions might not find it relevant to analyze outages in great detail, but such detailed outage analysis could be of great importance to other applications.

D. Better use of Qualitative Data

The insights from the HRA provide understanding of risk-significant areas and what can be done to reduce the likelihood of human error. This insight is not only important when making risk-informed decisions, but also when making investment decisions. It is not only the quantitative results from the HRA that provide insights; the qualitative results provide much useful information. Traditionally, HRA has mainly been used to provide human error probabilities to PRA and not much focus has been placed on the qualitative results. This is starting to change due to a better appreciation of the relationship between qualitative understanding of human behavior and increased safety in the industry.

Even though the appreciation for the importance of the qualitative data has increased, there is still room for improvement. The qualitative insights from the HRA will become even more important when using HRA in the design process. Even though the quantitative data from the HRA is needed for the PRA model, the qualitative insights will inform the system designers' decisions.

E. Human Reliability Analysis Design Acceptance Criteria

HRA is used in risk-informed decision making, and this should be extended to establishing operator performance thresholds. The goal of this extension would be to model deficits and their effects on system safety. Such limits, or thresholds, are useful in verifying system design. However, they should be introduced much earlier in the design phase.

The HRA verification considers performance to be a function of hardware and human actions. A system that has automated correction might prevent operators from learning from their errors. This could have consequences on plant safety if the operator makes the same error on a system without automatic correction. For design applications, HRA must identify these possible operator errors. In cases where high consequence errors are identified, HRA should provide design guidance for minimizing their occurrence.

F. Human Reliability Analysis Sensitivity to Human-Machine Interface Issues

HRA can be used to identify weaknesses in the human-system interface. This makes HRA a powerful tool. It is, however, important that the HRA method is sensitive to the different factors that influence the interaction between the operator and the system. HRA methods must adequately address digital instrumentation and control, advanced displays, and increased opportunity for automation. Since many of the existing methods are older than the technology used in the control room, or are based on data that were collected long before the era of digital instruments and control, it is essential that new HRA methods and tools be developed that are more attuned to advanced technology.

G. Better Integration of Human Reliability Analysis with Probabilistic Risk Assessment

HRA is an integral part of the PRA, both historically and today. Almost all HRAs are conducted as a part of a PRA. The main goal of HRA is not to perform a HRA in itself, but to provide high-quality quantitative and qualitative inputs to the PRA. HRA is a valuable part of the risk model and is therefore a key component to the PRA. HRA can be used outside the PRA, e.g., in the design phase or for spent fuel analyses. Nonetheless, quantifying human error is very context-dependent and the HRA needs to account for context. PRA can provide the context to the HRA.

The traditional interaction between PRA and HRA has diminished the importance of human actions in the model. It is essential to stop referring to HRA as a subpart of the PRA and instead start to think of HRA and PRA as equal partners. The human contribution to risk should be viewed as equally important as the contribution from hardware and software.

The HRA community currently has a strong emphasis on human factors and qualitative analyses, which is good. However, it is important to remember that HRA is still driven by PRA constraints, i.e., PRA must be able to use the HRA results in a suitable manner. One must also make sure that the two fields do not get too separated. By separating PRA and HRA, they might end up further away from where they can make an impact.

H. Need for Data to Support Human Reliability Analysis

The most common criticism of HRA is the lack of validated empirical data. Most of the HRA methods currently used are based on the human error probability data in THERP, which has not been fully validated and is now quite old. Therefore, there is no apparent way to justify whether the values used are appropriate.

There are different thoughts as to how data should be collected. Some argue that the data will only be valid if a large amount of data is collected under exactly the same conditions, while others argue that as long as the failure modes and mechanisms are clearly defined, data can be collected and applied in a wide variety of industries. Some argue that by using human performance modeling, the need for large amounts of data will be diminished. It might also be the case that, because of the inherent difficulty of collecting human performance data, the HRA community has to start to think about data in a new way. The lack of empirical data might suggest the use of ordinal ranking of human failure events instead of ascribing non-existing validity to the values themselves. Clearly, there is a great need to look into what kind of data the HRA community requires and what the best way is to collect it.

I. Human Reliability Analysis Method Development

There is a great need to further develop the human reliability field, and one of the distinct ways of doing so is to continue developing the methodology and the methods used. As discussed earlier, there is a need for tailored and scalable methods. There is also a need for methods that are adapted to address human-system interface and design issues. Methods should also incorporate new data and keep up to date with the human factors field. The main challenge to the HRA community will be to meet these criteria as along with the demand to keep the number of HRA methods to a minimum and make them easy to use. Therefore, the importance of this research must be recognized and the effort must be funded accordingly.

J. Communication

The HRA community must become more aware of the value of being able to communicate with allied disciplines such as human factors and PRA. There still are many misconceptions of what HRA is and what can be gained from such analyses. The HRA community must champion HRA in such a way that other fields understand it, if other fields are to start championing it themselves.

Even though HRA can be used to bridge the communication gap between human factors and the engineers in an organization, some of the terminology used in HRA can be hard for outsiders to understand. It is essential for HRA to communicate in a jargon-free manner in order to maintain the feedback loops between HRA and human factors and between HRA and PRA.

It is also important to improve the communication within the HRA community. Today, there is a communication gap between HRA researchers and HRA practitioners. They are almost two completely separate groups. This has to change if the HRA field is to improve. Researchers need to know the practitioners' real needs and the practitioners must understand why some research results can improve performance.

V. Conclusions

The list of principles provided in this report should be used as a complement to the list of principles provided in the Nordic Point of View study. The lists are similar, but the list in the Nordic Point of View study places more emphasis on HRA for design applications, while the list in this report emphasizes improvements to the HRA field more generally. The lists are not meant to be viewed as an exhaustive set of guidance principles, but as an attempt to aggregate all the HRA knowledge and experience in both the Nordic and the American nuclear power industries and their regulatory bodies into a framework that hopefully will be usable by the HRA community.

The list of principles presented in this report should be used as a starting point when discussing improvements to the HRA field. It is the author's intention that these principles will be useful both to HRA researchers and practitioners. The principles; *IV.A - Early Implementation in the Design Phase, IV.D - Better use of Qualitative Data, IV.E - Human Reliability Analysis Design Acceptance Criteria, IV.G - Better Integration of Human Reliability Analysis with Probabilistic Risk Assessment,* and *IV.J - Communication* are probably more of interest to HRA practitioners than the remaining principles, even though they can be helpful as well. The main incentive for improvements has to come from the industry and the regulatory body. It is essential that both feel ownership for the improvements since they are the ones affected by them.

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Abstract

The main goal of this Nordic Nuclear Safety Research Council (NKS) project is to produce guidance for how to use human reliability analysis (HRA) to strengthen overall safety. The project consists of two sub-studies: The Nordic Point of View – A User Needs Analysis, and The American Point of View – Insights of How the US Nuclear Industry Works with HRA. The purpose of the Nordic Point of View study was a user needs analysis that aimed to survey current HRA practices in the Nordic nuclear industry, with the main focus being to connect HRA to system design. In this study, 26 Nordic (Swedish and Finnish) nuclear power plant specialists with research, practitioner, and regulatory expertise in HRA, PRA, HSI, and human performance were interviewed. This study was completed in 2009. This study concludes that HRA is an important tool when dealing with human factors in control room design or modernizations.

The Nordic Point of View study showed areas where the use of HRA in the Nordic nuclear industry could be improved. To gain more knowledge about how these improvements could be made, and what improvements to focus on, the second study was conducted. The second study is focused on the American nuclear industry, which has many more years of experience with risk assessment and human reliability than the Nordic nuclear industry. Interviews were conducted to collect information to help the author understand the similarities and differences between the American and the Nordic nuclear industries, and to find data regarding the findings from the first study. The main focus of this report is to identify potential HRA improvements based on the data collected in the American Point of View survey.

Key words human reliability analysis; design; nuclear power plant

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