Extended Summary of NRC Involvement in the Halden Reactor Project

This attachment discusses in detail ongoing and planned work at the Organisation for Economic Co-operation and Development/Nuclear Energy Agency Halden Reactor Project (HRP) and the U.S. Nuclear Regulatory Commission's (NRC's) use of that work. The HRP includes a fuels and materials (F&M) program and a man-technology-organization (MTO) program, which together focus on nuclear fuel, nuclear reactor materials, human factors, human reliability analysis (HRA), and instrumentation and controls (I&C).

Nuclear Fuels

Reactor safety analyses rely on fuel damage criteria and computer codes that describe fuel rod behavior. These criteria and codes are used to ensure that significant fuel damage does not occur during normal operation, including anticipated transients, and that postulated accidents do not exceed established safety limits. These criteria and computer codes were originally developed from a database of mostly low-burnup fuel with Zircaloy cladding. The effects of high burnup (i.e., above 40 GWd/t) were noticed more than a decade ago, and research was initiated to investigate these burnup effects. As burnups in commercial reactors continue to increase and new fuel rod cladding alloys (like ZIRLO and M5) are introduced to reduce normally occurring corrosion, the regulatory criteria and evaluation models must be assessed to confirm their continued appropriateness. If the criteria and models are found to be inadequate or nonconservative, they must be modified in a way that the NRC finds acceptable.

The HRP conducts several significant fuels experiments in its boiling heavy-water reactor (HBWR), and the NRC uses the data gained to shed light on licensing and regulatory questions. The HRP's in-pile testing capabilities feature single rod experiments using a high-burnup fuel rod segment. Low-level nuclear power provides heat from within the rod to simulate decay heat and to produce short half-life fission products. By heating fuel rods from within, rather than externally, the HRP can simulate conditions closer to those of a power reactor. The HRP simulates thermal boundary conditions with an insulating channel and heated shroud. There is a spray system for steam supply, and it is possible to simulate both depressurizing and reflooding operations. In addition, by using independent experimental loops, the HBWR can simulate either boiling-water reactor (BWR) or pressurized-water reactor (PWR) conditions.

One of the HRP test series of particularly high interest to the NRC addresses conditions associated with loss-of-coolant accidents (LOCAs). These tests address the effects of burnup, rod pressure, cladding corrosion, and absorbed hydrogen on integral fuel behavior during a LOCA. The HRP has completed 12 tests in the current LOCA series and plans to conduct more in the upcoming program cycle. The HRP is uniquely able to run the in-reactor LOCA test and, after the clad ballooning occurs, to produce a radiophotograph of the fuel rod without disturbing its structure, thus extracting more precise information. The HRP's LOCA research directly informs the proposed rulemaking for Title 10 of the *Code of Federal Regulations* (10 CFR) 50.46, "Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Nuclear Power Reactors."

In addition, the HRP has conducted experiments on fission gas release. Utilities are seeking ways to suppress even minimal amounts of fission gas release from the fuel to the fuel-cladding gap, including redesigning fuel pellets to include various additives. In order to use such novel fuel pellets in power reactors, licensees will seek approval from the NRC. Thus, the HRP's fission gas release data will be of particular value in the review of new fuel designs.

Enclosure 3

Furthermore, the HRP conducted extensive research and discovered that burnup degrades fuel thermal conductivity. As this phenomenon had not been previously addressed, fuel codes were underpredicting (nonconservatively) fuel temperatures. The NRC applied this research to make significant changes to the agency's fuel performance codes described in NUREG/CR-6534, "FRAPCON-3: Modifications to Fuel Rod Material Properties and Performance Models for High-Burnup Applications". The NRC also issued a notice on nuclear fuel thermal conductivity degradation (Information Notice 2009-23, "Nuclear Fuel Thermal Conductivity Degradation," dated October 8, 2009), which encouraged utilities to make the necessary upgrades to their codes to address these effects in a timely manner.

Another example of the HRP's applicability to the NRC's mission dealt with mixed-oxide (MOX) fuel. Differences between uranium and MOX fuel were a central issue in a hearing in 2005 about the insertion of four lead test assemblies at Catawba. The contention was that the fuel behavior under accident conditions would be worse for MOX fuel than for standard fuel. Based on test data from the HRP, the NRC staff successfully argued that the differences would not be significant.

During the next 3 years, the HRP will continue research of high interest to the NRC in the area of fuel testing and performance. The upcoming program plan for the HRP has identified the following fuel-related activities:

(1) Studies Related to Gas Release under Irradiation
  - ultra-high burnup irradiation experiment
  - cladding lift-off experiments
  - fission gas release from standard, large grain, gadolinia, and chromia fuels
  - MOX helium release test

(2) Thermo-Mechanical Studies
  - fuel thermal conductivity degradation and recovery mechanisms
  - fission-induced fuel creep
  - gadolinia fuel behavior
  - VVER fuel behavior[1]
  - thermal behavior of modified fuels
  - integral fuel performance studies
  - cladding lift-off experiments

(3) Fuel Behavior under Accident Scenarios
  - LOCA test series

(4) Fuel Behavior under Demanding Operation Conditions
  - steady-state and transient creep of cladding
  - corrosion and hybriding of fuel cladding
  - In-core, online clad corrosion measurement techniques
  - power cycling/load follow behavior of high burnup fuel

(5) Innovative Fuels and Cladding
  - integral fuel performance studies of innovative fuels
  - characterization of the in-pile behavior of silicon carbide cladding

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[1] Vodo-Vodyanoi Energetichesky Reactor (VVER) is a type of PWR.

Nuclear Reactor Materials

The NRC's materials program maintains expertise in metallurgy, physical chemistry, and materials science to support the methods, data, standards, and tools used to evaluate the degradation of nuclear power plant structures and components. Specifically, the NRC focuses on the effects of corrosion and environmentally assisted cracking, irradiation effects (i.e., cracking, creep, stress relaxation), and steam generator tube integrity. In addition, the NRC is concerned with the material challenges for advanced reactors and the material degradation issues for operating nuclear power plants as they continue to age.

The HRP has provided fundamental technical information to support the understanding of the performance of irradiated reactor pressure vessel materials and to supplement the results generated under NRC research programs. The HRP has been an essential partner in evaluating the irradiation-assisted stress-corrosion cracking (IASCC) of light-water reactor materials. The HRP has irradiated materials that were later tested under the NRC's research program at Argonne National Laboratory to measure crack initiation, fracture toughness, and crack growth rate under representative light-water reactor conditions. The HRP has recently participated jointly with the NRC in the Cooperative IASCC Research Program (CIR), which is an international collaboration among utilities, vendors, regulators, and research organizations to develop IASCC data. The HRP also is using its unique facilities to simultaneously irradiate and test material susceptible to IASCC, stress relaxation, and creep. The HRP and CIR IASCC programs have provided information to supplement NRC-sponsored research and address existing knowledge gaps. The NRC staff is using this information to support the review and assessment of licensee aging management programs for reactor pressure vessel internals during license renewal. The HRP's evaluation of irradiation-induced stress relaxation is relevant for reactor pressure vessel bolting internals that must maintain preload to function properly under operational or transient conditions. The HRP's facilities are unique because they can measure the degree of relaxation as a function of irradiation fluence within the test reactor. The NRC currently is not sponsoring testing in this area and is relying on the HRP studies to support the staff's review and assessment of related aging management programs. Additionally, the NRC has also used results from the HRP materials testing program to provide part of the technical basis used to approve industry's plans for inspecting PWR reactor vessel internals. Evaluating the effects of irradiation on material performance is a costly endeavor. Participation in the HRP has enabled the NRC to reduce the high cost of irradiation and testing by sharing those costs with other signatories to develop the information needed to inform these licensing activities.

For 2012–2014, the HRP's materials program proposes to continue studying the effects of irradiation on reactor vessel internals as the age of operating nuclear power plants increases. The studies address the following plant aging and degradation issues:

- IASCC
- crack growth rates
- crack initiation (integrated time to failure)
- effectiveness of countermeasures to aging and degradation
- irradiation-enhanced creep and stress relaxation
- reactor pressure vessel embrittlement

Information from these studies will continue to be valuable to the NRC staff and will support the evaluation of industry's inspection and mitigation plans for ensuring the acceptable performance of reactor vessel internals during long-term operation.

Human Factors

10 CFR 50.34(f)(2)(iii) requires applicants to provide for Commission review a control room design that reflect state-of-art human factors principles. In order to verify that a design or a license applicant's implementation of a design will achieve the intent of the regulations, the NRC staff performs reviews at different points during the application and licensing processes. A primary goal of the Office of Nuclear Regulatory Research (RES) human factors program is to provide the NRC's regulatory review staff with tools and guidance, developed from the best available technical bases, to perform these reviews.

In order to develop and update the technical bases for review tools and guidance as well as rulemaking support, the RES human factors staff gathers and evaluates information from a variety of sources. These sources of information include operating experience and the human factors research literature from nuclear and nonnuclear domains, the activities of standards groups, and participation in bilateral agreements and international groups whose purpose is to share information. The HRP research results from Halden Man-Machine Laboratory (HAMMLAB) experiments provide a critical input to the process of developing review tools and guidance, particularly with respect to evaluating the applicability of research results from other domains, such as aerospace, to nuclear operations. The HRP's research efforts contribute to an improved technical basis for realistic safety decisions that will prepare the agency for the future by evaluating safety issues involving the introduction of new technology into existing control rooms and the impacts of new reactor designs and technologies on human performance.

A primary benefit of the HRP is its full-scope light-water reactor reconfigurable simulators. HAMMLAB currently has hardware and software enabling it to simulate the Fessenheim PWR plant in France, the Forsmark-3 BWR plant in Sweden, and the Ringhals-3 PWR plant in Sweden. The Ringhals-3 simulator is the most recent addition to HAMMLAB and is significant to the NRC because it is similar to a Westinghouse PWR. Many of the HAMMLAB experiments are performed with the control room configured as a prototype advanced control room with an integrated surveillance and control system. This setup is used to explore the impacts of automation and advanced human system interfaces on operator performance. HAMMLAB has extensive data collection capabilities and typically uses qualified nuclear power plant operators (who are familiar with the plants being simulated) as test subjects.

The NRC has used HRP research products as important inputs to the technical bases for review guidance on an array of topics, including alarm processing, filtering, integration, and prioritization (e.g., NUREG/CR-6684, "Advanced Alarm Systems: Revision of Guidance and Its Technical Basis," dated November 30, 2000). HRP research results also contributed to the technical bases for the review guidance in NUREG-0700, Revision 2, "Human-System Interface Design Review Guidelines," issued May 2002, on function allocation, human-centered automation, computer-based procedure functionality and approaches to procedure step tracking, use of large screen displays, display navigation, and impacts of hybrid control rooms on human performance. HRP products will continue to be an important source of information for the NRC as technologies used in the nuclear industry become more sophisticated and research needs progress. For example, the new reactor designs all propose the use of computerized procedures. As these proposals are becoming more concrete and immediate, the NRC staff needs revised guidance to better support safety reviews of these systems. Concurrently, the HRP is continuing research on automation, task-based displays, and soft controls. These research findings have supported development of an interim staff guidance memorandum on computerized procedures and will be incorporated in updates to NUREG-0700 and NUREG-0711, “Human Factors Engineering Program Review Model.”

During the next 3 years, the HRP will continue research of high interest to the NRC’s human factors research program for existing and new reactors. The upcoming program plan for the HRP has identified the following activities:

- Human and Organizational Factors
  - control room staffing in emergency situations
  - training of control room operators (assessment and improvement)
  - training in virtual and augmented reality environments
- Human-System Interfaces
  - innovative human-system interfaces for near-term applications
  - human-system interfaces to facilitate work practices in digital control rooms
  - human-system interface implementation techniques
- Control Center Design and Evaluation
  - the control center design process
  - improving the control room design process using virtual mockups
  - integrated system validation
- Outage and Field Work
  - human-system interfaces in outage control centers
  - teamwork in outages
  - visualization applications to support decommissioning activities
- Future Operational Concepts
  - highly automated plants
  - future control environments

A number of the activities in the next 3-year program involve the HRP’s virtual and augmented environment facilities, which provide opportunities for conducting research on the performance of tasks outside of the control room. These tasks include outage planning, maintenance training, and decommissioning, as well as alternatives to the traditional full-scope simulator for research on control room designs. For example, the HRP proposes to use the virtual environment center to explore advanced training techniques. It will investigate how instructional approaches and methods can be adapted to augmented reality and virtual reality training environments to develop innovative teaching methods. This research will include studying the instructor’s role in training based on virtual reality, and the effects of immersion and interactions. Information derived from this research will assist the NRC staff in evaluating the use of virtual reality for training, should current or future licensees propose such a change to existing approaches.

In addition to working with RES human factors staff to support the development of regulatory review tools, the HRP has also worked with the NRC staff to update NRC training and research facilities. HRP personnel worked with the NRC Technical Training Center (TTC) to enhance the NRC’s training simulators and enhance the TTC’s graphical user interfaces using the

HRP-developed Procsee system (a software tool for developing and displaying dynamic graphical user interfaces). The HRP assisted in the replacement of the NRC's BWR/4 simulator display system with a system of Window-based personal computers using the latest version of Procsee. An earlier similar joint project created a new display system for the NRC's Babcock and Wilcox simulator. The TTC continues to use the Nuclear Engineering Workstation Simulator, a classroom training tool originally developed with HRP assistance, during staff training. HRP personnel have also provided valuable insight into experimental design and measurement in simulation experiments. The NRC is able to leverage these insights for projects with other contractors and for upcoming work with the NRC's human performance testing platform.

Human Reliability Analysis

In accordance with the 1995 NRC Probabilistic Risk Assessment (PRA) Policy Statement, the NRC should increase its use of PRA technology in all regulatory matters to the extent supported by the state of the art. HRA supports PRA in the evaluation of the overall risk for which human actions can be significant. It is therefore important to appropriately characterize the human failure events modeled in a PRA and assess failure event probabilities. However, experts view HRA as an area that contributes significantly to the uncertainties of PRA results. NUREG/CR-6903, Volume 1, "Human Event Repository and Analysis (HERA) System, Overview," states, "…HRA is therefore considered as among the most uncertain portions of a [nuclear power plant] risk assessment by PRA practitioners and decision makers. Today's risk-informed regulatory approach in the commercial nuclear industry demands that the uncertainties in HRA be reduced or at least be better understood." Because of its long history in performing studies on topics related to human factors, the HRP has the capability, facilities, and expertise to conduct simulator experiments and collect data that can be applied to HRA modeling and quantification issues.

One source of uncertainty from HRA comes from the differences among HRA methods that result because the methods were developed by different individuals and organizations, and some were built to serve slightly varying purposes. In addition, HRA methods are characterized by high-level guidance rather than strict prescriptive formulas; thus, interpretations can range. It is therefore necessary to understand these differences to better support PRA. The HRP helped address this critical issue through the International HRA Empirical Study, a multinational study aimed at developing an empirically based understanding of the performance, strengths, and weaknesses of HRA methods used in risk-informed regulatory applications.

The HRP supported this study by first designing four potentially risk-significant scenarios, two variations of a steam generator tube rupture and two variations of a loss of feedwater accident, and testing these scenarios with 14 Swedish crews in HAMMLAB. Fifteen HRA teams from 10 countries predicted how the crews would perform. An independent assessment team then evaluated these predictions against the empirical data obtained in HAMMLAB. The NRC published the first of three reports documenting the findings from this study as NUREG/IA-0216, Volume 1, "International HRA Empirical Study—Phase 1 Report," issued November 2009. It was also published as an HRP work report in 2009. These reports focused on the results of the steam generator tube rupture scenarios. A report focused on the loss of feedwater scenarios and a report on the overall lessons learned are forthcoming.

The NRC has made particular use of this HRA study both in terms of its methodology as well as its conclusions. The NRC staff worked with the HRP staff and employed the International HRA Empirical Study methodology to design the U.S. HRA Empirical Study. The U.S. study was intended to further validate the results of the international study for U.S. crews. While the methodology was the same as that of the international study, the domestic study used fewer crews and different scenarios that were adapted to and conducted at a U.S. plant. In addition, the U.S. study used fewer HRA teams and methods, but it used multiple teams per method to address analyst-to-analyst variability. The HRP's original study provided the platform for the NRC to further explore or confirm specific questions and findings.

The International HRA Empirical Study highlighted several key findings. First, the assessment team noted that the variability in qualitative analysis was an important contributor to variability in HRA results. Additionally, the assessment team concluded that HRA teams and methods tended to underrate potential challenges for procedure-driven human actions as well as inconsistencies in judgments of performance-shaping factors and in treatment of dependencies. These results supported an assessment of HRA methods that produced practical insights that the NRC can specifically use as input to answering Staff Requirements Memorandum (SRM)-M061020, dated November 8, 2006. This SRM directed the Advisory Committee on Reactor Safeguards to "work with the staff and external stakeholders to evaluate the different Human Reliability models in an effort to propose either a single model for the agency to use or guidance on which model(s) should…be used in specific circumstances." The conclusions from the HRP study are a resource for the project outlined in the SRM. For example, one of the goals of the team for that project is to ensure that there is clear qualitative guidance for the proposed method(s).

The HRP continues to focus on HRA as a main research area of its MTO program and provides significant benefits to the NRC. Notably, during summer 2010, the HRP hosted an NRC staff member for a 4-month rotation at its facilities in Halden, where she focused on the upcoming HRA study. This rotation served to greatly enhance the staff member's understanding of HRA and the HRP's experimental process and facilities, and to aid in her responsibilities as HRP project manager. The HRP is well equipped to support such rotations since it has a "secondee" program that allows guest researchers from all of the member countries to partake in short-term assignments at the HRP. In addition, during summer 2011, the HRP used six U.S. nuclear plant operations crews as test subjects for its current HRA study on modeling cognitive systems in emergency response scenarios. This is the first time in the project's history that U.S. crews have participated in a HAMMLAB study, which is a testament to the ever-strengthening working relationship the HRP has developed with the NRC and U.S. utilities.

During 2012–2014, the HRP has proposed to focus on the following HRA activities:

- improving scenario analysis for HRA (case studies of HRA practice)
- modeling operator behavior in emergency response
- resilient procedure use

Instrumentation and Controls

The NRC digital I&C program develops and applies methods, data, tools, standards, and guidance to assess the adequacy of digital I&C systems. The NRC's digital I&C research program spans the development of regulatory guidance and its technical basis for safety and security, including knowledge management through international collaboration. In the HRP's 2012–2014 research plan, the NRC is primarily interested in the research related to safety cases.

Past HRP efforts related to I&C include work in the area of instrumentation surveillance and monitoring techniques based on advanced decision algorithms. The latter have included techniques for core monitoring, condition monitoring of electrical cables, and early fault detection in process systems.

In recent years, the HRP has expanded its research efforts in digital systems safety. The HRP's past digital I&C research focused on the front end of the software development cycle, primarily on the areas of formal methods for the review of requirements, and the integration of diagnostics into plant control systems. As a result of HRP and related activities at the Norwegian Institutt for Energiteknikk to develop operational support systems for the HBWR, commercial reactor applications, and HAMMLAB, the HRP staff also has acquired the skills and knowledge to develop and test digital systems.

For the next 3-year cycle, the HRP has organized its digital systems research into three aspects: the dependability of software systems, condition monitoring and maintenance support, and operation support. The HRP's research program on software systems dependability will contribute to the successful development, assurance, and deployment of high-integrity software within the nuclear sector through better processes, methods, techniques, and tools. The research program on condition monitoring and maintenance support will improve the accuracy and usability of current methods and the development of novel techniques to better support diagnostic activities and condition-based maintenance strategies.

Since the HRP's I&C program is reorganizing its structure, this new program cycle is an opportunity for increased alignment between the NRC's and the HRP's I&C research.

Schedule of HRP Events

The HRP operates on a 3-year research cycle. The next program plan runs 2012–2014. Preparations for a new cycle begin roughly a year and half before its start. During a program cycle, the HRP facilitates many occasions and formal meetings for knowledge exchange, and both the NRC and the HRP find it very beneficial to arrange for additional individual visits. The official interactions facilitated by the HRP include the following:

- Enlarged Halden Program Group meetings: Held every 1.5 years. Each meeting is a large technical conference that covers all of the HRP's current F&M and MTO research projects.

- Halden Program Group meetings: Held biannually. F&M and MTO representatives from each signatory country meet to discuss technical issues.

- Halden Board meetings: Held biannually. Representatives from the signatory countries meet to discuss and resolve high-level management issues.

- Halden summer schools: Held annually. The schools hold 1-week seminars on various technical topics to teach and train newer staff.

- Secondees program: Member organizations can send staff to the HRP for short-term rotations.

The HRP first proposed its research plan for 2012–2014 in June 2010. Since then, the NRC has provided substantial feedback to the HRP and ranked the proposed activities on a scale of importance.   The HRP's final proposal aligns well with the NRC's priorities.