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 that together focus on nuclear fuels, nuclear reactor materials, human factors, and digital instrumentation and controls (I&C).

Nuclear Fuels

Reactor safety analyses rely on fuel damage criteria and computer codes that describe and assess fuel rod behavior. These criteria and codes are used to ensure significant fuel damage does not occur during normal operation, including anticipated transients, and that the effects due to 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 adverse effects of high burnup (i.e., above 40 GWd/MTU) were noticed more than a decade ago, and research was initiated to investigate these burnup effects. As burnups in commercial reactors continue to gradually 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 non-conservative, they must be modified to NRC's review and acceptance.

The HRP conducts several significant fuels experiments in its boiling heavy-water reactor (HBWR), and the NRC uses such data to provide information to address licensing and regulatory questions. The HRP's in-pile testing capabilities feature multiple single rod experiments in isolated and controlled experimental loops, many of which use high-burnup fuel rod segments from commercially irradiated fuel rods. 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 as is the case in many other experimental programs, 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 14 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 *in situ* 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. 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 and assessment of new fuel designs.

Moreover, 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) that encouraged utilities to make the necessary upgrades to their codes to address these effects in a timely manner. In the interim, penalties were imposed in the analysis if codes were not upgraded to account for thermal conductivity degradation.

Another example of the applicability HRP's research to NRC's need is the experiments 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 nuclear power plant (NPP). 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) Integral Fuel Performance
- Long-term irradiation of VVER fuel
- Fission gas release mechanisms
- Long-term Irradiation of doped/additive fuels
- Integral performance of high burnup fuel

(2) Separate Effects Fuel Behavior Studies
- Fuel thermal conductivity degradation and recovery mechanisms
- Fission and temperature induced fuel creep

(3) Fuel Behavior in Transients and under Accident Scenarios
- Fuel behavior under LOCA conditions
- Behavior of high-burnup-structure fuel
- Performance of medium/high burnup fuel subjected to transients

(4) Cladding Performance and Behavior
- Steady state and transient creep of cladding
- Corrosion and hydrating of fuel cladding
- Corrosion, creep, and growth of candidate accident tolerant fuel claddings

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. The HRP has provided fundamental technical information to support the understanding of the performance of irradiated reactor pressure vessel materials and has supplemented 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. Irradiation-assisted degradation data generated under the HRP have supplemented NRC-sponsored research and address existing knowledge gaps.

The HRP's evaluation of irradiation-induced stress relaxation is relevant for reactor pressure vessel bolting internals that must maintain the 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 other testing in this area and is relying on the HRP studies to support the staff's review and assessment of related aging management programs.

Evaluating the effects of irradiation on material performance is a significant time- and resource-consuming endeavor. Participation in the HRP has enabled the NRC to reduce the high cost of irradiation and testing by sharing those costs with other HRP participants to develop the information needed to inform licensing decisions. NRC staff has encouraged the HRP to focus on identifying high fluence austenitic stainless steel specimens for IASCC testing to provide maximum value and relevance to NRC regulatory needs. NRC staff will work with the HRP to potentially provide materials harvested from the Zorita plant for testing at the HRP. This will allow high-priority research for the NRC to be performed efficiently through the highly leveraged HRP program. Information from these studies will continue to support the review and assessment of licensee aging management programs for reactor pressure vessel internals during license renewal.

For 2015–2017, 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 upcoming program plan for the HRP has identified the following materials-related activities:

(1) Irradiation-Assisted Stress Corrosion Cracking
- Crack growth rate as a function of fluence, temperature, stress, and water chemistry
- Effect of water chemistry, stress, and fluence on crack initiation
- Assessment of post-irradiation heat treatment on IASCC susceptibility
- Microstructural characterization of irradiated materials

(2) Irradiation Enhanced Creep and Stress Relaxation
- Creep and stress relaxation of alloys commonly used in LWRs
- Creep and stress relaxation of candidate replacement materials

(3) Pressure Vessel Integrity Study
- Small punch test and mini-tensile specimens irradiated in Halden reactor for Slovakian power reactors

Human Factors and Reliability

10 CFR 50.34(f)(2)(iii) requires applicants to provide, for Commission review, a control room design that reflects state-of-the-art human factors principles. To verify that a design or a license applicant's implementation of a design will meet the intent of the regulations, the NRC staff performs reviews at different points during the license application process. A primary goal of the Office of Nuclear Regulatory Research (RES) human factors and human performance program is to provide guidance, based upon scientific state-of-the-art technical bases, for regulatory review of licensee submittals. To develop and update the technical bases, the RES staff gathers and evaluates information from a variety of sources. These sources include operating experience and research literature from nuclear and nonnuclear domains, the activities of codes and standards bodies, and participation in bilateral agreements and international organizations. The HRP research results provide valuable input to the process of developing NRC technical bases and guidance.

A primary benefit of the HRP is its full-scope light water reactor reconfigurable simulators. HAMMLAB currently has hardware and software 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 a recent addition to HAMMLAB and is noteworthy to the NRC because the design is similar to a Westinghouse PWR. Many of the HAMMLAB experiments are performed with the control room configured as a prototype of an advanced control room. 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 licensed NPP operators who are familiar with the plants being simulated as research participants.

Associated with the simulation infrastructure is HRP's highly qualified and knowledgeable research team along with 30 years of organizational knowledge in conducting human-in-the-loop simulation studies. Conducting complex human performance simulation experiments requires integration of multidisciplinary knowledge in the areas of computer software/programming, NPP operation and scenarios, human performance, and experimental psychology. The HRP has developed a strong integrated research team to perform high-fidelity and in-depth human performance research. Over the years, they have also developed various reconfigurable experimental interfaces that enable them to quickly adapt the existing interfaces to meet the needs of new studies. In recent years, the HRP has begun using U.S. NPP operations crews, including a crew from the NRC Technical training Center, as test participants for its human performance studies. This recent development of U.S. crews participating in HRP studies is a testament to the ever-strengthening working relationship the HRP has developed with the NRC and U.S. utilities.

Another benefit of the HRP is access to the international NPP community it provides. This allows the HRP researchers to perform studies in the international community and to provide the member organizations lessons learned on NPP safety with a broad scope. For instance, the HRP performed a safety culture study by collecting data from four different countries. The results revealed great similarity across the different countries regarding the effect of safety culture on operator performance. The results verified the importance of safety culture and provided a number of lessons learned on how to effectively implement safety culture.

Another example of HRP's role as an international collaborator is the HRP's integrated system validation (ISV) study. The ISV process is important to safe operation of plants because it provides reasonable assurance that the integrated plant systems, including human-system-interfaces (HSI), procedures, and operating crews, can achieve the expected functions and do not pose significant threats to the safe operation of the plant. The HRP worked with member organizations that have access to plants with newly built or upgraded control rooms and conducted an ISV. The HRP staff consolidated the lessons learned from those plants and developed initial metrics for performing an ISV. In addition to research projects like these, the HRP also routinely organizes workshops on specific topics for experts in the international community exchanging information, identifying issues and research needs in the area, and developing new research plans. In summary, the HRP serves as a platform that effectively and efficiently fosters international collaborations for its member organizations.

In recent years, the HRP's human reliability analysis (HRA) research has provided information of high value to the NRC's risk-informed regulatory activities. HRA supports probabilistic risk assessment (PRA) in the evaluation of the overall risk for which human actions can be significant. Therefore, it is important to appropriately characterize the human failure events modeled in a PRA and to assess failure event probabilities.

One fundamental issue in HRA is the uncertainties associated with various HRA methods and practices. The Staff Requirements Memorandum dated November 8, 2006 related to a meeting with the Advisory Committee on Reactor Safeguards on October 20, 2006 directed the staff to address HRA method uncertainties. As a result, NRC staff teamed with the HRP and other member organizations to conduct the landmark International HRA Benchmarking Study with multiple teams from different countries testing a set of HRA methods and comparing the testing results to actual operator performance on the same scenarios with the HRP's simulators. The results provided empirical data for HRA as well as raised awareness and interest in HRA in the international nuclear community. As a follow-on to the International Benchmarking study, the HRP conducted a U.S. HRA empirical study using U.S. operators in a U.S. plant that provided valuable inputs to the NRC's HRA research and practices.

HRP's 2015-2017 human factors research program has six sections: human reliability, human and organizational factors, HSI, control-room design and evaluation, outage and field work, and future operational concepts. Overall, the research examines human performance aspects and human factors considerations in the usage of existing and new technologies and operational concepts. Traditional HAMMLAB studies have focused on normal/off-normal operations.

Following the Fukushima event, HRP member organizations desired studies of human performance in the areas of emergency operating procedures (EOPs), unusual events, and severe accidents. Such studies may be limited or challenged by the HRP's current simulator capabilities. However, HAMMLAB's ongoing study on resilient procedure use is transitioning HRP's human performance experiments into the areas of emergency and severe accident operations. With EOP scenarios, HAMMLAB staff explores human performance issues caused by the same cognitive challenges as those that would be faced by operators in severe accidents. The NRC is very interested in these studies and has been working closely with the HRP staff to ensure this research will be useful to the NRC.

In addition to EOP and severe accident research, the HRP has developed a cohesive research program in the area of HRA with several projects addressing different aspects of HRA practices including scenario analysis, modeling, experimental testing, and data collection. These projects are interrelated and together could contribute to advances in HRA practices. The research in other sections of the HRP's human factors program provides inputs to inform the technical basis of the NRC's human factors review guidance, including NUREG-0700 "Human-System Interface Review Guidelines" and NUREG-0711 "Human Factors Engineering Program Review Model."

This input is especially important for the NRC's review of new technologies and design in control rooms because the NRC staff needs to understand their impact on operators' performance and the resulting safety implications. For example, the HRP's study of HSI design has demonstrated several advantages of increasing the size of operator workstation displays from 19 to 30 inches, especially related to improved navigation. Another study showed that reducing control-room staffing from the current level would lead to some safety concerns under emergency operations.

A new addition to the MTO facility is the Future Operation Concept Laboratory. The newly formed laboratory develops prototypes and demos of new technologies and concepts. It integrates development, testing, and evaluation capabilities to identify human performance issues in the new technologies and concepts and recommend solutions. For example, the laboratory demonstrated the coordination between control room operators with field operators using touch-screen displays. The laboratory has the potential to study the boundary conditions of using new technology with respect to safety, identify unsafe impacts of new technologies on plants, and develop solutions to address some current safety considerations such as using the new technologies to provide field operators peer-checking. Generally, in HRP's human factors program, it is challenging to the HRP to determine how to best utilize the existing facilities to address safety and how to balance exploring future design concepts with addressing regulators' safety concerns with new/advanced technologies. The NRC staff has been and will continue to closely interact with the HRP to include safety aspects in HRP's human factors research projects.

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. In particular, the HRP continues to focus on HRA as a main research area of its MTO program and is expected to provide significant benefits to the NRC. The upcoming human factors research program plan for the HRP has identified the following activities:

(1) Human Reliability Analysis
- The Halden Project HRA database
- Improving HRA practice
- Emergency and severe accident operation

(2) Human and Organizational Factors
- Emergency preparedness organizations
- Training control room operators for accident management
- Safe shut down during control room and station blackout
- Transition from normal to emergency operation

(3) Control Room Design and Evaluation
- Integrated system validation
- Human system interfaces for near-term applications
- Verification and validation using virtual mockups

(4) Outage and Field Work
- Next-generation outage control centers

(5) Future Operational Concepts
- Future interfaces and human-automation teams

(6) Decommissioning
– Techniques for optimizing decommissioning strategies
– Ubiquitous computing to support field work
– Visualization technologies to support briefing and training

Digital Instrumentation and Controls

The NRC's 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 2015–2017 research plan, the NRC is primarily interested in the development of a safety demonstration framework.

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 in 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.

HRP's digital systems research proposal for 2015-2017 is broken into two broad categories: software systems dependability and operation and maintenance support. NRC's primary interest in this area is the development of a safety demonstration framework, which is being addressed by the HRP through its research area of software systems dependability. In the current program period, the HRP has coordinated international expert elicitations and hosted a workshop at the NRC in March 2014 on the topic of safety demonstration framework. These activities lay the groundwork for further HRP development to address the challenges and to identify best practices for digital I&C system safety demonstration consistent with the Digital I&C Research Plan. Safety demonstration methodologies would be highly valuable to the NRC as the technical basis for regulatory guidance development.

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.

The upcoming program plan for the HRP has identified the following digital systems-related activities:

(1) Software Systems Dependability
– Digital I&C requirements
– Digital I&C assurance
– Digital I&C approval

(2) Operation and Maintenance Support

– Performance monitoring models
– Diagnostic decision support
– Condition-based maintenance
– Collaboration technology for safe use of computerized procedures

Schedule of HRP Events

The HRP operates on a 3-year research cycle. The next program plan runs 2015–2017. 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. 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 18 months. 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 2015–2017 in June 2013. 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 reasonably well with the NRC's priorities.