

EXPANDED SUMMARY OF U.S. NUCLEAR REGULATORY COMMISSION'S INVOLVEMENT IN THE HALDEN REACTOR PROJECT

This enclosure discusses in detail ongoing and planned work at the Organisation for Economic Co-operation and Development Nuclear Energy Agency's 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 that performs research in the Halden Boiling-Water Reactor (HBWR) on nuclear fuels and nuclear reactor materials and a Man-Technology-Organization (MTO) program that performs research in the areas of human factors and digital instrumentation and control (I&C).

Nuclear Fuels

Reactor safety analyses rely on fuel damage criteria and computer codes that describe and assess fuel rod behavior under a range of operating conditions. These criteria and codes are used to ensure that significant fuel damage does not occur during normal operation, including anticipated operational occurrences, and the effects of 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 higher burnup (i.e., above 40 gigawatt-days per metric ton of uranium) 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 as new fuel rod cladding alloys (like Optimized ZIRLO™ and M5™) are introduced to reduce normally occurring corrosion, the regulatory criteria and evaluation models must be assessed to confirm their continued adequacy. If the criteria and models are found to be inadequate or nonconservative, they must be modified for the NRC's review and acceptance. The HRP provides the data necessary to assess the criteria and models in NRC's fuel performance codes. Today, over half of the assessment cases used to validate the NRC's steady-state fuel performance code, FRAPCON, were derived from Halden tests. The HRP also provides independent fuel performance information used by the NRC staff in reviewing topical reports for new fuel designs.

The HRP conducts several significant fuels experiments in the HBWR, and the NRC uses this independent data source in the review of fuel topical reports and to support licensing and regulatory reviews. 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 in many other experimental programs), the HRP can simulate conditions closer to those of nuclear fuel in 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 the conditions in either a boiling-water reactor (BWR) or pressurized-water reactor (PWR).

One of the HRP test series of particular interest to the NRC evaluates 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 only burnup-dependent LOCA tests used to validate NRC's transient fuel performance code, FRAPTRAN, are Halden tests. The HRP has completed 16 tests in the current LOCA

series and plans to conduct more tests in the upcoming program cycle (2018-2020). The HRP is uniquely able to run the in-reactor LOCA test and to produce a radiograph of the fuel rod after the clad ballooning occurs without disturbing the structure of the rod, thus extracting more precise in situ information. The HRP's LOCA research directly informed the draft final rulemaking for Title 10 of the *Code of Federal Regulations* (10 CFR) 50.46c, "Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Nuclear Power Reactors" (SECY-16-0033).

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 and larger grains. To use such novel fuel pellets in power reactors, licensees will seek approval from the NRC. Thus, the NRC has used HRP's fission gas release data to review and assess fuel topical reports related to the performance benefits for these novel pellets.

Moreover, Halden has the unique ability to measure real-time fuel temperatures, which has led to the development of FRAPCON's fuel relocation model as well as the discovery of fuel thermal conductivity degradation (TCD). As the TCD 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. The NRC also issued Information Notice 2009-23, "Nuclear Fuel Thermal Conductivity Degradation," dated October 8, 2009, to encourage utilities to make the necessary upgrades to their codes to promptly address the effects of nuclear fuel TCD.

Accident-tolerant fuel (ATF) experiments are another example of how the NRC has used HRP's research to help fulfill the NRC's needs. Because the international fuel community has largely agreed that Halden is the premier reference test reactor, demonstration of ATF in the Halden reactor is one of the highest priorities for many fuel vendors. The HRP is expected to provide the only source of in-reactor, online fuel center-line temperature measurements for ATF, which are critical to the validation and assessment of fuel performance models and licensing safety evaluation. Additionally, the HRP can provide online measurements of rod internal pressure, which is another critical requirement for assessing integral rod behavior, thermal/mechanical deformation, and fission gas release.

During the next three 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 three fuel-related activities:

- (1) Long- and Short-Term Fuel Performance Irradiations
 - Long-term irradiation of enhanced performance fuels
 - BeO [beryllium-oxide] doped UO₂ [uranium oxide] fuel
 - Short-term irradiation of preirradiated fuel rods
 - Fission induced fuel creep
 - High-burnup structure development
- (2) Fuel Properties and Behavior Related to Transient and Accident Conditions
 - Fuel behavior under LOCA conditions
 - Behavior of HBS [high-burnup structure] fuel during transients

- Transient fission gas release
 - Dry-out
 - Power cycling
- (3) Cladding Performance and Behavior
- Cladding creep
 - Cladding corrosion under high Li [lithium] environment
 - Long-term irradiation of ATF cladding
 - Fuel cladding behavior in interim dry storage

Nuclear Reactor Materials

The NRC's materials research 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 (NPP) structures and components. The HRP supports the NRC's materials research by providing experimental data on the irradiation-assisted degradation (IAD) of reactor vessel internals materials. Research on highly irradiated reactor internals materials is a very resource-intensive effort due to the large expense associated with handling highly irradiated materials and the limited experimental facilities available to support such research.. 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. IAD data generated under the HRP supplement NRC-sponsored research and help address existing knowledge gaps for extended plant operation and subsequent license renewal.

The NRC staff has previously encouraged the HRP to prioritize irradiation-assisted stress-corrosion cracking testing of high-fluence austenitic stainless steel specimens to maximize the value and relevance of HRP work to NRC regulatory needs. The NRC staff has worked with the HRP and the Electric Power Research Institute to provide highly representative plate and weld materials harvested from the José Cabrera Nuclear Power Station (also referred to as the Zorita plant) for irradiation and testing at the HRP. Very limited data are currently available on the properties of stainless steel weld materials under irradiation; therefore, information from the further irradiation and testing of the Zorita plant weld materials will directly address a key gap for subsequent license renewal and will support the review and assessment of licensees' aging management programs for reactor vessel internals.

The HRP's evaluation of irradiation-induced stress relaxation is relevant for reactor vessel internals bolting. Loss of bolt preload may play an important role in bolt failures, such as the recent operating experience of significant baffle-former bolt failures in some U.S. PWRs. 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.

The HRP's pressure vessel integrity research is focused on irradiation of small punch test (SPT) and mini tensile specimens for a reactor in Slovakia. This work is not of high interest or relevance to the NRC as U.S. plants use Charpy test specimens to monitor reactor pressure vessel embrittlement.

During the next three years, the HRP's materials program will continue to focus on the IAD of reactor vessel internals. The upcoming program plan for the HRP has identified the following materials-related activities:

- (1) Irradiation-Assisted Stress Corrosion Cracking
 - Crack growth rate studies
 - Crack initiation studies
- (2) Irradiation Enhanced Creep and Stress Relaxation
- (3) Pressure Vessel Integrity Study

Human Factors and Reliability

Under 10 CFR 50.34(f)(2)(iii), the Commission requires applicants to submit 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 human factors and human performance program in the Office of Nuclear Regulatory Research is to provide guidance based on scientific state-of-the-art technical bases for the regulatory review of licensee submittals. To develop and update the technical bases, the 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. The Halden Man-Machine Laboratory (HAMMLAB) currently has hardware and software to simulate the Fessenheim Nuclear Power Plant PWR in France; the Forsmark Nuclear Power Plant, Unit 3, BWR in Sweden; and the Ringhals Nuclear Power Plant, Unit 3 (Ringhals-3), PWR in Sweden. The Ringhals-3 simulator is a recent addition to HAMMLAB, which the NRC finds noteworthy 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 effects of automation and advanced human-system interfaces (HSIs) on operator performance. HAMMLAB has extensive data collection capabilities and typically uses as research participants licensed NPP operators who are familiar with the plants that are being simulated.

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 assembled a strong integrated research team to perform high-fidelity and in-depth human performance research. Over the years, the HRP has also developed various reconfigurable experimental interfaces that enable it 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 participation of U.S. crews in HRP

studies is a testament to the ever-strengthening working relationship that the HRP has developed with the NRC and U.S. utilities.

Another benefit of the HRP is its access to the international NPP community. This access allows the HRP to perform studies in the international community and to provide the member organizations lessons learned on NPP safety with a broad scope. For example, the HRP performed a safety culture study by collecting data from four different countries. The results revealed great similarity in the effects of safety culture on operator performance among the different countries. The results verified the importance of safety culture and provided a number of lessons learned on how to effectively implement a positive safety culture that enables safe operation.

Integrated system validation (ISV) studies are another example of the HRP's role as an international collaborator. The ISV process is important to the safe operation of plants because it provides reasonable assurance that the integrated plant systems, including HSIs, 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 ISV. The HRP staff consolidated the lessons learned from those plants and developed initial metrics for performing ISV. In addition to research projects like these, the HRP also routinely organizes workshops on specific topics for experts in the international community to exchange information, identify issues and research needs in the area, and develop new research plans. In summary, the HRP serves as a platform that effectively and efficiently fosters international collaboration 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 determine failure event probabilities.

One fundamental issue in HRA is the uncertainties associated with various HRA methods and practices. In a November 8, 2006, staff requirements memorandum (SRM-M061020), the Commission directed the staff to address HRA-method uncertainties. As a result, the NRC staff teamed with the HRP and other member organizations to conduct a 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 and 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.

The HRP's 2018–2020 human factors research program has four primary areas: (1) operator reliability, (2) severe accidents and human performance, (3) control room design and evaluation, and (4) future operational concepts. Overall, the research examines human performance aspects and human factors considerations in the use 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 wanted 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, the HAMMLAB's recent study on the use of resilient procedures is transitioning HRP's human performance experiments into the areas of emergency and severe accident operations. With EOP scenarios, the HAMMLAB staff explores human performance issues caused by the same cognitive challenges as those that operators in severe accidents would face. The NRC is very interested in these studies and has been working closely with the HRP staff to ensure that this research will be useful to the agency.

In addition to EOP and severe accident research, the HRP has developed a cohesive HRA research program 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 Design Review Guidelines," issued May 2002, and NUREG-0711, "Human Factors Engineering Program Review Model," issued November 2012. 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 the impact of such technologies 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 48 to 76 cm (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 FutureLab. This laboratory develops prototypes and demonstrations of new technologies and concepts. It integrates development, testing, and evaluation capabilities to identify human performance issues in the new technologies and concepts and to recommend solutions. For example, the laboratory demonstrated the coordination between control room operators and 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 the unsafe effects of new technologies on plants, and develop solutions to address some current safety considerations, such as using the new technologies to provide peer checks on field operators. Generally, within its human factors program, the HRP finds it challenging to determine how to best use the existing facilities to address safety and how to balance exploring future design concepts with addressing regulators' safety concerns about new and advanced technologies. The NRC staff and the HRP will continue to work closely together to include safety aspects in the HRP's human factors research projects.

During the next three years, the HRP will contribute 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) Operator Reliability
 - Operator Reliability in Digital Control Rooms
 - Operator Reliability for Actions Outside the Control Room
 - The Human Performance Data Repository

- (2) Severe Accidents and Human Performance
 - Decision Making with Severe Accident Management Guidelines
 - Operator Fatigue in Intense, Complex Scenarios
 - Performance Impact of Free or Fixed Operator Position
- (3) Control Room Design and Evaluation
 - Design Approach to Support Multi-Stage Control Room Modernization
 - Human Performance Evaluation in System Validation
 - The Impact of Overview Displays on Human Performance
- (4) Future Operational Concepts
 - Human-Automation Collaboration in Future Plants
 - Interactive Human-System Interfaces for Future Operations
 - Operation of Multiple Small Modular Reactors (SMRs)

Digital Instrumentation and Controls

The HRP’s digital systems research proposal for 2018–2020 has three primary areas: (1) safety and security in digital I&C design, (2) human factors and digital I&C, and (3) digital I&C safety demonstration. The NRC’s primary interest is in the areas of both safety and security in digital I&C design and digital I&C safety demonstration. The HRP research can provide important insights related to the technical basis for some of the critical design challenges, such as defense against common cause failure in the deployment of digital I&C at U.S. reactor facilities. During interactions with the HRP, the staff prioritized these areas as high and exchanged various ways and ideas for the HRP to embark on research on design issues that have been a significant challenge to the nuclear industry. The HRP has indicated their desire to collaborate with the agency and other members in this area for initiatives for research. The HRP performed a case study, in the current program period, of the safety argumentation in a recent licensing submittal to the NRC. This case study reviewed the submittal for explicit reasoning to demonstrate independence as needed for safety. The study found the submittal had no logical reasoning or argument to demonstrate independence but was, rather, primarily a design description. The HRP also coordinated a workshop hosted at the NRC in March 2017 on the topic of digital I&C safety assurance; the workshop generated a useful discussion and was well attended by industry, regulators, and other research organizations. These activities lay the groundwork for further HRP work in this area to address the challenges and to identify best practices for digital I&C system safety demonstration. Using a method similar to that of the case study can identify potential gaps in the technical basis and regulatory criteria. Both areas provide opportunities for enhancing the agency’s strategic modernization of the I&C regulatory infrastructure improvements¹, and this supports further research of high value to the NRC and other HRP members. During a meeting with the HRP staff held on August 16, 2017, the NRC staff expressed this interest and developed a list of the expected deliverables from this effort in support of the aforementioned modernization plan.

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

¹ See Modernization Plan 4B of the Integrated Action Plan (ML16097A182).

- (1) Safety and Security in Digital I&C Design
- (2) The Human Factors of Digital I&C Methodologies
- (3) Digital I&C Safety Demonstration

From these three activities, the NRC staff is interested in the areas of both safety and security in digital I&C design and digital I&C safety demonstration. Specifically, the outcomes from the activities have the potential to support the efforts of the agency's Digital I&C Integrated Action Plan to modernize the I&C regulatory infrastructure.

Schedule of HRP Events

The HRP operates on a 3-year research cycle. The next program plan runs from 2018–2020. Preparations for a new cycle begin approximately 1.5 years before it starts. During a program cycle, the HRP facilitates formal meetings and provides many other occasions 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. F&M and MTO representatives from each signatory country meet biannually to discuss technical issues.
- Halden Board Meetings. Representatives from the signatory countries meet biannually to discuss and resolve high-level management issues.
- Halden Summer Schools. The schools hold annual 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. Two NRC staff have previously performed rotations of a few months in length at Halden under this program.

The HRP first proposed its research plan for 2018–2020 in April 2016. 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.