EXTENDED SUMMARY OF NRC INVOLVEMENT IN THE HALDEN REACTOR PROJECT

This enclosure discusses ongoing and planned work at the Halden Reactor Project (HRP) in the areas of nuclear fuel, nuclear reactor materials performance, human factors, human reliability analysis (HRA), and digital instrumentation and control (I&C) systems, and how the work has been used at the NRC.

The HBWR is fully dedicated to instrumented in-reactor testing of fuel and reactor materials. It also delivers steam to a nearby paper factory. Since its initial startup, the reactor facility has been progressively updated and has now become one of the most versatile test reactors in the world. In the course of this development, more than 300 in-reactor experiments have been performed. The HRP fuels and materials program focuses on the performance of fuel and structural materials under normal or accident conditions using the large number of experimental channels in the core that are capable of handling many test rigs simultaneously.

IFE's Halden facility also includes the IFE Man-Technology-Organization (MTO) Laboratory. The Halden Man-Machine Laboratory (HAMMLAB) is one of the principal experimental facilities in this laboratory. The HAMMLAB uses a reconfigurable simulator control room that facilitates I&C, human factors, and human reliability analysis (HRA) research. Currently, HAMMLAB has hardware and software enabling it to simulate the Fessenheim pressurized-water reactor (PWR) plant in France and the Forsmark-3 boiling-water reactor (BWR) plant in Sweden. The HAMMLAB is the only Western-style light-water reactor (LWR) reconfigurable simulator that is available to NRC for human factors research.

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. The 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 IFE MTO Laboratory also includes a virtual environment center and an integrated operations laboratory. The former is used to perform research involving mixed reality applications (e.g., training) and the latter is used to address issues associated with remote operations. The laboratory has a large staff that conducts research on a wide range of technical disciplines and is an acknowledged center of excellence in the nuclear arena.

<u>Nuclear Fuels</u>:

For nuclear fuels, the HRP performs experiments to develop data needed to address current issues. Fuel damage criteria and computer codes that describe fuel rod behavior are used in reactor safety analyses. Criteria and codes are used to ensure fuel integrity during normal operation, including anticipated transients, and to ensure that postulated accidents do not evolve into core melt scenarios. These criteria and computer codes were originally developed from a database of mostly low-burnup fuel with Zircaloy cladding. The HRP fuel program is addressing the effects on this database of longer fuel burnup times, new materials that are being used to achieve high burnups, and mixed-oxide (MOX) fuel that will be used for plutonium disposition in the United States. Data from the HRP fuel program have been employed directly in recent NRC reviews of industry fuel behavior codes. These data also are used in updating NRC's fuel codes and materials properties library, which is used to audit industry analyses.

In addition, the fuel properties and codes are used in assessment of spent fuel storage and transportation.

Regarding the HRP's 2009-2011 nuclear-fuels-related activities, NRC is particularly interested in ongoing fuel rod Loss of Coolant Accident (LOCA) tests that it, along with the Electric Power Research Institute (EPRI) and France, has championed since 2000. Recent Halden tests have confirmed for high-burnup fuel that oxygen can diffuse into the cladding metal during a LOCA from the inside diameter (ID) as well as from the outside diameter, even when no steam oxidation is occurring on the ID. These tests supported an NRC Research Information Letter on cladding embrittlement.[1] The HRP 2009-2011 tests will investigate such phenomena as axial gas flow, integrity of fuel-to-cladding bonding, fuel axial relocation, and fuel fragment spillage through cladding burst opening. It should be noted that the HBWR is well-suited for in-pile integral tests on fuel behavior under LOCA conditions where the decay heat is simulated by a low level of nuclear heating. This provides data under conditions that are more realistic than those associated with out-of-reactor tests in hot cells.

<u>Nuclear Reactor Materials Performance</u>:

Over the years, the HRP has provided fundamental technical information to support the understanding of the performance of irradiated reactor pressure vessel (RPV) materials and supplement results generated under NRC research programs. Recently, the HRP has been an essential partner in evaluating the irradiation-assisted stress corrosion cracking (IASCC) of LWR materials. The HRP has irradiated materials that were later tested under NRC's research program at Argonne National Laboratory to measure crack initiation, fracture toughness, and crack growth rate under representative LWR conditions.

Currently, the HRP is participating jointly with 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. The HRP and CIR IASCC programs provide information that supplements the NRC-sponsored research and addresses existing knowledge gaps. The NRC staff is using this information to inform reviews of licensee aging management programs for RPV internals during license renewal.

In 2009-2011, in addition to the aforementioned IASCC work, the HRP will continue its ongoing evaluation of irradiation-induced stress relaxation. This phenomenon is relevant for RPV bolting internals that must maintain preload to function properly under operational or transient conditions. HRP's unique facilities will be used to measure the degree of relaxation as a function of irradiation fluence. The NRC currently is not sponsoring testing in this area and is relying on the HRP program to provide information to support the staff's review of aging management programs. The HRP also will continue to support NRC's ongoing efforts to evaluate RPV integrity by participating in an International Atomic Energy Agency (IAEA) round robin to develop surrogate test procedures for evaluating the fracture toughness of RPVs.

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[1] U.S. Nuclear Regulatory Commission, "Technical Basis for Revision of Embrittlement Criteria In 10 CFR 50.46," Research Information Letter 0801, May 30, 2008.

In summary, participation in the HRP has enabled the NRC to reduce the high cost of irradiation and testing by sharing of costs with other signatories. Also, the HRP continues to provide technical information through activities designed to supplement NRC-sponsored research by addressing existing knowledge gaps related to irradiated material performance.

Human Factors:

The HRP's MTO program conducts experiments related to human error, human performance, teamwork, and the effects of computer-driven interfaces using IFE's HAMMLAB and virtual environment facilities. The results of HRP research have served as a part of the technical bases for regulatory guidance to aid staff reviews of issues such as the potential impacts on operator performance of control room modernization projects (including challenges to operator performance associated with navigating through computerized displays) and potential staffing configurations in computer-based control rooms or from remote locations that may differ from required configurations in current plants. The results of HRP human factors research also have been integrated into Chapter 18, "Human Factors Engineering," of the Standard Review Plan (NUREG-0800); NUREG-0700, Rev. 2, "Human-System Interface Design Review Guidelines"; NUREG-0711, Rev. 2, "Human Engineering Program Review Model"; and, most recently, draft review guidance addressing computer-based procedures, manual operator actions, and the minimum inventory of controls and displays needed if computer-driven interfaces are unavailable as a result of a common-cause failure. The staff uses these guidance documents to evaluate changes to control stations at current reactors, design certification applications for new reactors, and license amendment requests. The staff also has used this guidance during plant inspections.

The HRP's 2009-2011 plans for human factors research address a number of topics of interest to NRC. These topics include further research on control room staffing strategies and the role and effects on human performance of automation in advanced control room designs. HRP will also perform new research on operator aids to improve teamwork and supervision in computer-based control rooms. The staff expects that the results of HRP's 2009-2011 research will provide important contributions to the technical bases for NRC human factors guidance, particularly guidance for the review of new reactor designs.

Human Reliability Analysis:

As discussed in a recent OECD/NEA report, the international HRA community recognizes that empirical data are needed to reduce the reliance of current HRA predictions on expert judgment. During the 2006-2008 agreement period, the HRP MTO program has performed important research addressing this need. In particular, this program has provided critical support to 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 study involves HRP-designed and executed HAMMLAB experiments involving 14 operating crews responding to 4 potentially risk-significant scenarios, "blind" predictions of crew performance by 15 HRA teams from 13 countries, and comparisons of the predictions against the experimental data by an independent group of HRA experts. The pilot phase of the study, completed in 2008, has provided insights as to how HRA practices can be improved. For example, it has shown where improved guidance is needed for the use of current HRA methods. NRC will be using the study's results to address outstanding HRA technical issues, including those related to HRA model differences identified in a November 8, 2006, staff requirements memorandum (SRM) (SRM-M061020).

Similar to other HRP activities, the resources NRC has committed to the HRP Empirical Study represent only a fraction of the actual cost of the study because the HRP is providing experimental facilities, expertise, and test subjects without additional cost to participating signatory organizations. Moreover, under the HRP's auspices, numerous organizations (including EPRI) are participating (without cost to NRC) in developing predictions or in analyzing these predictions. In addition, Halden is entering the human performance data generated by the study's experiments into NRC's Human Event Repository and Analysis (HERA) system, a database intended to support NRC's HRA activities.

For the upcoming 2009-2011 agreement period, the HRP MTO program plans to continue performing HAMMLAB experiments with a focus on HRA. In addition to addressing specific HRA needs, these experiments will create an empirical basis for addressing issues related to specific accident sequences and issues that are of regulatory importance, such as steam generator tube rupture, feed and bleed, and loss of offsite power. The NRC staff is working closely with the HRP staff to ensure that research conducted in the HAMMLAB will be risk informed and will result in data and information that NRC can use to improve HRA methods and practices.

<u>Digital Instrumentation and Controls</u>:

The HRP has been conducting I&C research for a number of years. Past efforts 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. A number of HRP-developed systems have been evaluated for use by U.S. plants.

In recent years, the HRP has expanded its research efforts in digital systems safety. 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 review of requirements, and integration of diagnostics into plant control systems. As a result of HRP and related activities to develop operational support systems for the HBWR, commercial reactor applications, and the HAMMLAB, Halden also has acquired the skills and knowledge to develop and test digital systems. For example, Halden has established a software engineering laboratory (SElab) that provides the systems and resources needed to support research, development, assessment, consultancy, and training related to safety-oriented software engineering.

HRP's 2009-2011 digital I&C research program focuses on software systems dependability issues related to the engineering and architecture of digital safety systems. Two of the HRP-identified metrics of dependability are reliability and correctness; the HRP will investigate their importance at various phases in a system life cycle. Specific areas of research are requirements engineering, fault tolerance and error propagation, and dependability assessment. The NRC staff has interacted with HRP during the development of the 2009-2011 program to ensure that the HRP work complements NRC research activities, particularly with regard to analysis of failure propagation. With continued focus on tangible products (e.g., software tools, review guidance, and objective acceptance criteria), the staff believes that the research products generated from the HRP research over the next few years will complement NRC's own research in improving the technical bases for safety decisions regarding current and new digital system designs and technologies for safety-related applications.

Other Related Halden Work:

In the past, IFE's Halden staff has worked with the NRC Technical Training Center (TTC) to enhance the NRC training simulators and build on the TTC's graphical user interfaces using the Halden-developed Procsee system (a software tool for developing and displaying dynamic graphical user interfaces). Halden most recently provided assistance in the replacement of the NRC's BWR/4 Simulator display system with a system running on Windows-based PCs using the latest version of Procsee. An earlier similar joint project resulted in a new display system on the NRC's Babcock and Wilcox (B&W) Simulator. The TTC's Nuclear Engineering Workstation Simulator (NEWS), a classroom training tool originally developed with Halden assistance, continues to be used during staff training and is being upgraded by NRC personnel using the latest version of Procsee.

The NRC staff is working toward the development of a training simulator that will be similar to the simulator in the HAMMLAB. This training simulator will support both digital human-machine interface and new reactor operations training. The concept includes a choice of simulated reactor models and a reconfigurable advanced control room. In support of this effort, NRC staff would consult with Halden on the design, integration, and operation of such a simulator, leveraging on HRP's HAMMLAB experience. Halden's work with the TTC will be conducted outside of the HRP.