POLICY ISSUE
(Information)

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FOR: The Commissioners

FROM: Brian W. Sheron, Director
Office of Nuclear Regulatory Research

SUBJECT: NRC PARTICIPATION IN THE HALDEN REACTOR PROJECT DURING 2015-2017

PURPOSE:

The purpose of this memorandum is to inform the Commission of the results of the U.S. Nuclear Regulatory Commission's (NRC's) past participation in the Halden Reactor Project (HRP) and the staff's plans to continue participating in the project during 2015–2017.

SUMMARY:

The HRP is a cooperatively funded international research and development project that operates under the auspices of the Organisation for Economic Co-operation and Development's Nuclear Energy Agency (OECD/NEA). The HRP is located in Halden, Norway, and managed by the Norwegian Institute for Energy Technology (Institutt for Energiteknikk). The international organizations actively participating in the HRP represent a cross section of the nuclear community: licensing and regulatory authorities, national research organizations, reactor and fuel vendors, and utilities. The U.S. HRP membership is divided between the signatory member, the NRC, and associated parties General Electric/Global Nuclear Fuel, Westinghouse Electric Company, Electric Power Research Institute, and the U.S. Department of Energy. Both signatory members and associated parties provide funding to the HRP and receive all research results and data, but only signatory members hold voting rights on the Halden Board of Management for their country. Associated parties may be observers to the Halden Board, and are encouraged to provide technical input into the proposed program of research at Halden.

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The HRP research programs address four primary areas: (1) nuclear fuels, (2) irradiation-assisted degradation of nuclear reactor materials, (3) digital systems, and (4) human factors. Results and information from HRP research directly support program office user need requests and Commission-directed activities. Participation has also maximized use of NRC research funds by leveraging the resources of other HRP participants. In addition, participation in the HRP facilitates cooperation and technical information exchange with the participating countries. The staff plans to continue to participate in the project for the 2015–2017 agreement period because of the highly leveraged research benefits in key technical areas, as well as the excellent opportunity for international cooperation and information exchange.

BACKGROUND:

The NRC and its predecessor, the U.S. Atomic Energy Commission, have participated in the HRP since its inception in 1958. The HRP membership has expanded over the years and currently includes 31 organizations from 20 countries (Enclosure 1). The HRP plans its program in 3-year agreement periods. The current agreement expires at the end of the calendar year 2014, and the upcoming cycle covers the period from 2015–2017. In advance of each 3-year program, Halden prepares a research proposal detailing the planned areas for the upcoming 3-year period. The research proposal is provided to HRP member organizations for review. HRP also visits each member organization to formally present the proposal and to discuss how the proposal could be improved for each member's needs. HRP members provide feedback by ranking each proposed project to communicate their preferences for the direction and approach of the specific proposed projects. HRP reconciles this feedback and uses it to prioritize its activities.

The HRP is organized into two parallel research programs: the fuels and materials (F&M) program and the Man-Technology-Organization (MTO) program. The F&M program focuses on nuclear fuels and nuclear reactor materials performance through tests conducted in the Halden Boiling Water Reactor (HBWR). The HBWR supports instrumented in-reactor testing of fuel and reactor materials using numerous experimental loops that run through the reactor core. Since its initial startup, the reactor facility has been progressively updated and currently contains multiple loops to simulate both boiling-water reactor (BWR) and pressurized-water reactor (PWR) environments. Fuels research includes loss-of-coolant accident (LOCA) testing, fission gas release studies, and fuel and cladding creep experiments. Materials research projects focus on irradiation-assisted stress corrosion cracking tests, stress relaxation, and creep experiments for reactor internals materials.

The MTO program focuses on digital instrumentation and control (I&C) systems, human factors, and human performance. The HRP uses nuclear power plant (NPP) simulators, a virtual environment, and an integrated operations laboratory to support this research. For instance, the Halden Man-Machine Laboratory (HAMMLAB) includes a reconfigurable simulator control room with hardware and software to simulate PWR and BWR plants in France and Sweden. HAMMLAB recently added new simulators to simulate U.S. Westinghouse PWR designs. The HAMMLAB conducts human performance research generally using operators from Sweden. In recent years, the laboratory also has started to use operators from U.S. plants and recently included staff from the NRC's Technical Training Center. The broad insights derived from the Halden simulator experiments have general applicability to U.S. research for the purposes of better understanding and improving human performance.

The HRP has been endeavoring to coordinate their research programs and the needs of member organizations through frequent interactions. The Halden Board of Management (HBM) meets semiannually to provide project oversight and review and to decide whether to approve or disapprove the HRP's plans. HBM consists of representatives from signatory members (no more than one per country). Mr. Richard Correia, Director of RES's Division of Risk Analysis, is currently the NRC's voting representative on the HBM. The Halden Program Group (HPG) also meets semiannually and provides a technical advisory forum for member organizations to give technical recommendations to the HRP. The NRC technical staff members serve as representatives on the HPG and interact with HRP to ensure the agency's research needs are represented in HRP projects. They also collaborate with representatives from other member organizations to provide input regarding the scope and focus of research to HRP.

DISCUSSION:

The NRC has benefited from participation in the HRP because the research results have supported regulatory products, leveraged limited nuclear safety resources, supported knowledge transfer to the NRC staff, and supported the NRC's international communication, coordination, and collaboration efforts. By taking part in this multinational research agreement, the NRC leverages its resources to collect a large amount of valuable data. Involvement in the HRP also supports knowledge transfer to the NRC staff through visits to the HRP facilities and rotational opportunities. The HRP is well equipped to support such rotations through its secondee program that allows guest researchers from all of the member countries to partake in short-term assignments at the HRP. NRC has previously sent junior staff on rotation to Halden in the areas of fuels and human factors to gain a deeper understanding of the research performed at Halden. Finally, participation in the HRP provides an ideal venue for cooperation and information exchange with international counterparts.

During the current 2012-2014 program period, the NRC has received the benefit of many research products from HRP. Enclosure 2 provides a listing of HRP reports for the 2012-2014 time period (those reported up to October 2014 are included in this listing). The following subsections briefly describe the benefits derived by the NRC from past and continued participation in the HRP for each area of work. Enclosure 3 provides a more detailed discussion of these areas along with examples of regulatory products.

Nuclear Fuels

Fuel damage criteria and computer codes that describe fuel rod behavior are used in reactor safety analyses. These criteria and codes are used to ensure fuel integrity during normal operation (including anticipated transients) and to ensure that fuel subjected to postulated accidents does not exceed established safety limits. These criteria and computer codes were originally developed from a database largely related to low-burnup fuel with Zircaloy cladding. The HRP fuel program is enhancing this database by addressing the effects of longer fuel burnup times, new fuel and cladding 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 staff reviews of industry fuel behavior codes. These data, which take several years to gather, are also essential for updating the NRC's fuel codes and materials properties library to support audits of industry safety analyses. The fuel properties and codes also are used to assess spent fuel storage and transportation. Of particular interest to the NRC is the HRP's extensive LOCA test series that enhanced NRC's fuel code calculations and directly informed 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". During the next 3 years, the

HRP will continue research of high interest to the NRC in the area of fuel testing and performance.

Nuclear Reactor Materials

The HRP has provided fundamental technical information, which supplements the results generated under NRC research programs to better understand the performance of irradiated reactor internals materials. The HRP has been an essential partner in evaluating the irradiation-assisted stress-corrosion cracking (IASCC) of light-water reactor (LWR) materials. The staff used HRP facilities to irradiate 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 LWR conditions. The NRC staff uses such data to inform its license renewal reviews of licensee aging management programs for reactor pressure vessel internals, which includes technical input for the guidance in the Generic Aging Lessons Learned report. The NRC also has used the information from the HRP materials testing program to provide part of the technical basis for the review of industry's plans to inspect PWR reactor vessel internals. Over the next 3-year period, the HRP plans to continue irradiated material testing, which will augment the technical basis for assessing the structural integrity of reactor vessel internals during potential subsequent license renewal periods.

Human Factors

The HRP's human factors research program has six sections: human reliability, human and organizational factors, human-system-interfaces (HSI), control-room design and evaluation, outage and field work, and future operational concepts. Overall, the research examines aspects of human performance and human factors considerations in new and existing nuclear plants, and the usage of new and existing technologies. The results of HRP research have served as a part of the technical basis for NRC regulatory guidance for reviewing changes to control rooms for operating reactors, new reactor applications, license amendment requests, and plant inspections. Key guidance documents whose development and updating have been supported by HRP research include NUREG-0700 "Human-System Interface Review Guidelines" and NUREG-0711 "Human Factors Engineering Program Review Model." For instance, the MTO program has been closely working with the NRC and other international organizations on collecting human reliability data, which provided benchmarking for the NRC's development of improved human reliability methods. In addition, the HRP's integrated systems validation project has provided useful information for the NRC's effort to update human factors review guidance in this area. During the next 3 years, the HRP will continue research of high interest to the NRC, particularly in the area of human reliability analysis.

Digital Instrumentation and Controls

HRP's digital systems research has 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 that 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 a workshop hosted at the NRC in March 2014 on the topic of developing a safety demonstration framework for digital I&C systems. These activities lay the groundwork for further HRP development to address the challenges and to identify best practices for safety demonstration. Safety demonstration methodologies directly support NRC's Digital I&C Research Plan and are of high value for developing regulatory guidance.

Halden Agreement

The Halden Agreement is an OECD/NEA agreement that describes the terms and conditions of participation in the Halden Reactor Project. NRC staff has engaged with the HRP on various areas of potential improvement to the Halden Agreement. These areas include clarification of the rights and responsibilities of signatory members and associated parties, procedures for recruitment of new members and distribution of Halden research results, and transparency in the proposal ranking process and the financial contributions of associated parties. NRC staff has been pleased with the level of engagement from the HRP on a number of these issues and continues to work with the HRP and other HRP members to continue to make progress in these areas. In addition, NEA has encouraged Halden to update the Halden agreement to be more consistent with other NEA agreements. Therefore, as recommended by the HBM, the HRP has made significant updates to the Halden Agreement for the upcoming 2015-2017 period to address some of the areas for improvement described above.

Halden Reactor License Renewal

The Norwegian nuclear regulatory authority has recommended approval of a renewed license for the HBWR to continue operating from 2015 through 2024. Final approval of the renewed license is expected by the King of Norway before the end of 2014. In the unlikely scenario that the operating license for the HBWR is not renewed, the NRC staff will take appropriate action regarding NRC's participation in HRP during 2015-2017. The status of the HBWR's license renewal will be known prior to NRC providing any funding for the 2015 – 2017 period.

RESOURCES:

The cost of the NRC's participation in the HRP during the 2012–2014 agreement period was 33 million Norwegian kroner (NOK). HRP's initial request to HRP members was for a 10-percent increase in contributions for the 2015-2017 period. According to the HRP, a roughly 10-percent increase every 3 years is needed to maintain the same level of effort to cover higher costs due to inflation and cost-of-living increases in salaries and benefits. At the June 2014 HBM meeting, HRP presented a 2015-2017 program plan with no increase in fees. Under this plan, lower priority projects in all areas would be suspended.

The Halden Board of Management came to a unanimous decision of no increase in fees due to economic conditions among HRP members. Therefore, the cost of the NRC's participation in the HRP during the 2015–2017 agreement period is 33 million Norwegian kroner (NOK). This amounts to a total obligation of about $1.72 million per year given an exchange rate of 6.41 NOK to the dollar[1].

$2.0 million has been budgeted each year in the FY 2015 and FY 2016 budget requests. Funding for FY 2017 will be addressed through the agency's Planning, Budgeting, and Performance Management (PBPM) process. The FY 2015 and FY 2016 funds are located in the Research Product Line of the Operating Reactors Business Line.:

[1] The exchange rate of 6.41 NOK to the dollar was calculated on September 17, 2014. Within the last year, the exchange rate has ranged from 5.75 to 6.42 NOK to the dollar, which corresponds to an annual NRC contribution range of $1.71M to $1.91M.

COORDINATION:

The Office of the Chief Financial Officer has reviewed this paper for resource implications and has no objections. The Office of the General Counsel has no legal objection to this paper. The Office of International Programs has no objections to this paper.

/RA/

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Enclosures:
1. Members of the Halden Reactor Project
2. Listing of Halden Reports for 2012-2014
3. Extended Summary of NRC Involvement in the Halden Reactor Project

Members of the Halden Reactor Project

The members of the Halden Reactor Project (HRP) include both signatory members and associated parties as listed below. Each country that is part of the Organisation for Economic Co-operation and Development has one signatory member in the HRP, and an unlimited number of associated parties can join the HRP. Both signatory members and associated parties provide funding to the HRP and receive all research results and data. Signatory members have representatives on the Halden Board of Management and the Halden Program Group and have voting rights. Representatives from associated parties may attend meetings of the Halden Board of Management and the Halden Program Group and provide input, but the final vote on issues addressed by those bodies rests only with signatory members.

Signatory Members

- **Norway:** Norwegian Institutt for Energiteknikk (IFE)
- **Belgium:** Belgian Nuclear Research Center (SCK/CEN)
- **Czech Republic:** Czech Nuclear Research Institute (NRI, UJV-Rez)
- **Denmark:** Technical University of Denmark (DTU)
- **Finland:** Finnish Ministry of Employment and the Economy (VTT)
- **France:** Électricité de France (EDF)
- **Germany:** Gesellschaft für Anlagen- und Reaktorsicherheit mbH (GRS)
- **Hungary:** Hungarian Center for Energy Research, Hungarian Academy of Sciences (MTA EK)
- **Japan:** Japanese Nuclear Regulation Authority (NRA)
- **Korea:** Korean Atomic Energy Research Institute (KAERI)
- **Russia:** Joint-Stock Company TVEL
- **Slovak Republic:** Slovakian Nuclear Power Plant Research Institute (VUJE)
- **Spain:** Spanish Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT)
- **Sweden:** Swedish Radiation Safety Authority (SSM)
- **Switzerland:** Swiss Federal Nuclear Safety Inspectorate (ENSI)
- **United Arab Emirates:** Federal Authority for Nuclear Regulation (FANR)
- **United Kingdom:** National Nuclear Laboratory Limited (NNL)
- **United States:** U.S. Nuclear Regulatory Commission

Associated Party Members

- **European Union:** Joint Research Center Institute for Transuranium Elements
- **France:**
  – Institut de Radioprotection et de Sûreté Nucléaire (IRSN)
  – Le Commissariat à l'Energie Atomique et aux Energies alternatives (CEA)
- **Japan:**
  – Japan Atomic Energy Agency (JAEA),
  – Central Research Institute of Electric Power Industry (CRIEPI)
  – Mitsubishi Nuclear Fuel LTD (MNF)
- **Kazakhstan:** Ulba Metallurgical Plant
- **United States:**
  – General Electric/Global Nuclear Fuel
  – Westinghouse Electric Company
  – Electric Power Research Institute
  – U.S. Department of Energy

Listing of Halden Reports for 2012-2014

REPORTS FROM THE FUELS AND MATERIALS PROGRAM 2012-2014	
HPR-377	Comparison of Halden Zry-4 corrosion tests
HPR-380	Overview of Halden LOCA tests: evaluation report
HWR-1028	Coatings and plasma treatments for nuclear applications
HWR-1032	Crack growth rate tests for austenitic stainless steels
HWR-1033	Characterization of KKL BWR Fuel for Test Series in IFA-610, IFA-629, and IFA-650
HWR-1038	The Gadolinia fuel test IFA-681: Overview of in-pile measurements from beginning of irradiation to unloading
HWR-1039	The fuel creep test IFA-701: results after four irradiation cycles
HWR-1040	Status report on the fission gas release test IFA-716
HWR-1041	Fission gas release of high burnup fuel disks in IFA-629.6
HWR-1042	The BWR LOCA test IFA-650.13: in-pile measurements
HWR-1043	Radioactive iodine and cesium release measurements
HWR-1044	PIE on the test rod from LOCA test IFA-650.12
HWR-1045	Results from the second interim inspection of the PWR cladding corrosion test IFA-708
HWR-1046	Results from the online PWR cladding corrosion test IFA-731
HWR-1047	Update on the stress relaxation test IFA-669
HWR-1049	Core physics calculations for the Halden Reactor
HWR-1072	Minutes of IASCC review meeting 17-18 October 2012
HWR-1074	Minutes of workshop meeting on the Halden LOCA test series IFA-650, Lyon 2012
HWR-1075	Minutes of workshop on “Data needs and testing ideas for demanding operation conditions and innovative fuels and claddings”
HWR-1079	Final Report on the BWR Crack Growth Rate Investigation IFA-745
HWR-1080	Data uncertainties in experiments and 1odeling – workshop minutes
HWR-1085	Observations on creep in molybdenum and some other refractory metals and alloys
REPORTS FROM THE MAN-TECHNOLOGY-ORGANIZATION PROGRAM 2012-2014	
HPR-373	The International HRA Empirical Study – Final Report – Lessons Learned from Comparing HRA Methods Predictions to HAMMLAB Simulator Data
HPR-379, Vol 1	Proceedings of the Man-Technology-Organization Sessions
HPR-379, Vol 2	Proceedings of the Man-Technology-Organization Sessions
HWR-995	Emergency procedures and crew behavior: A retrospective test of the Guidance-Expertise Model
HWR-996	Work Practices and New Technologies –iPad as a Tool for Shift Supervisor to Monitor Process Information

HWR-1000	Stakeholder Communication and Motivational Aspects in Decommissioning Processes
HWR-1002 rev. 2	Towards Approaches for Analysis and Argumentation for Systems Safety and Security: Comparison of Techniques and Conceptual Model
HWR-1027	Cross-cultural Generalizability in the Nuclear Domain: A Comparison of Culture Profiles for Control Room Operators in Swedish, Korean. and U.S. Plants
HWR-1029	A Pattern-based Method for Safe Control Conceptualization – Exemplified within Nuclear Power Production
HWR-1030	New Computational Model for Areal and Personal Monitoring in Nuclear Environments
HWR-1031	A Method to Support Control Room Design Process Using Virtual Mockups
HWR-1034	Workshop Meeting on Human Performance Measurement for Simulator Experiments In Nuclear Process Control
HWR-1035	Teamwork Quality in Nuclear Power Plant Control-Room Crews
HWR-1036	Lessons Learned and Recommendations on Software Development
HWR-1037	A Pattern-based Method for Safe Control Conceptualization – Exemplified within Railway Signalling
HWR-1050	Software Safety Approval
HWR-1051	HALDEN RM – Supporting the Management of Traceability
HWR-1052	SaCS-PL-A Language for Specification of Pattern Composition
HWR-1053	Traceability of Safety Systems: Approach, Meta-model and Tool Support
HWR-1054	Requirements Elicitation – Completeness, Traceability, and Automation
HWR-1055	Product- and Process-oriented Failure Analysis
HWR-1056	Software Safety Demonstration
HWR-1057	Combined Safety and Security Assessment: Presenting the CHASSIS Method
HWR-1058	Assessing and improving accuracy of physical models using data reconciliation and statistical techniques
HWR-1059	Functional Representation of Process Operation with Multilevel Flowmodels for Diagnostic Decision Support
HWR-1060	Lifetime Models Based on Degradation Data and Randomly-distributed Failure Thresholds
HWR-1061	Advanced Control and Automation Support – The Development of the MFM Editor and its Application for Supervision, Diagnosis and Prognosis
HWR-1062	Just-in-time Assessment of Procedures by Computer Simulation
HWR-1063	A Measurement Framework for Human Factors Integrated System Validation of NPP Control Rooms
HWR-1064	1st Experiment for the Development of Criterion Referenced Approach to Human Factors Integrated System Validation (ISV)
HWR-1065	A State-based Alarm System for HAMBO

HWR-1066	Summary of the 2012 Workshop on Human System Interfaces
HWR-1067	Unified HSI Concepts for Near-term Applications: Design Philosophy and Concept Proposal
HWR-1068	Collaboration Surface for Offshore Maintenance Planning in the Petroleum Industry – Lessons Learned from the “Scenario Composer” Research Prototype
HWR-1069	Preliminary Insights on HRA Scenario Analysis from the U.S. HRA Empirical Study and HRA Interviews
HWR-1070	Integrated Operations for Outages – Lessons Learned from the Petroleum Industry
HWR-1071	HSI in Outage Control Centers: Summary of Field Studies
HWR-1073	Evaluating Usability of the Information Rich Design Concept: Using the Halden Reactor Large Screen Display and Old Replaced Panels
HWR-1076	Case Studies of Methodological Approaches to Performance based Evaluation of Nuclear Power Plant Control Rooms
HWR-1078	Workshop Meeting on Using Simulator Data to Improve Human Reliability Analysis
HWR-1082	Team Self-Assessment Tool (TESA)
HWR-1083	A Method for Formal Verification
HWR-1103	Study on the Use of Virtual Mock-ups and Automated Verification Assistance to Support Human Factors Review Process
HWR-1104	Design Concept for HSI Guideline Tool
HWR-1105	A Mobile Computing System for Monitoring of Maintenance Activities
HWR-1108	Study on Use of a Virtual Plant for Supporting the Inclusion of Plant Field Personnel in Simulation and Training
HWR-1109	Nuclear decommissioning support from A to Z based on 3D simulation and advanced user interface technologies
HWR-1112	Safety Demonstration and Justification of DI&C Systems for NPPs - Elicitation Interviews with Regulators
HWR-1113	Summary of the 2014 Expert Workshop on Safety Demonstration and Justification of Digital Instrumentation and Control systems in Nuclear Power Plants
HWR-1114	Product- and Process-oriented Failure Analysis – Method and Techniques Combination
HWR-1115	Data-driven Techniques for Condition-based Maintenance
HWR-1116	Life-time Estimation Models of Air Filters for Nuclear Power Plants
HWR-1117	Advanced Control and Automation Support – The Continued Development of the MFM Suite
HWR-1118	Practical Application of the MFM Suite on a PWR System: Modelling and Reasoning on Causes and Consequences of Process Anomalies
HWR-1119	Issues relating to the design and implementation of portable procedure systems

HWR-1120	Improving Scenario Analysis for Human Reliability Analysis (Draft Report)
HWR-1121	Diagnosis and Decision-Making with Emergency Operating Procedures: A HAMMLAB Study with U.S. Operators
HWR-1124	Control Room and Field Operator Cooperation – Use of a Handheld Tool
HWR-1126	Modernization Experiences in Nuclear Power Plants' Control Rooms (Draft Report)
HWR-1127	A Day of an Outage: Visions for the Future
HWR-1128	Highly Automated Plants: Perspectives, Methods and Prototypes
HWR-1129	The Plant Panel: Feasibility Study of an Interactive Large Screen Concept for Process Monitoring and Operation

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:

- <u>Enlarged Halden Program group meetings</u>: 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.

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

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

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

- <u>Secondees program</u>: 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.