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U.S. NRC Perspectives on the Halden Reactor Program

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Thank you for inviting me to speak here today. It is an honor to address this group of researchers from around the world. I am encouraged to see this degree of international cooperation in the Halden Reactor Program.

I'm the newest Commissioner at the NRC, and with that in mind I'd like to provide you with a sketch of my background. From that background, I think you'll understand why I am particularly enthusiastic about the work of the Halden Program.

My graduate training focused on experimental nuclear physics and its applications to astrophysics. I spent 15 of my roughly 30 years at Los Alamos supporting experimental plasma diagnostic measurements. From that work, I acquired an appreciation for the significant challenges associated with the translation of basic research and engineering knowledge into real systems. Those experiences also taught me to have a healthy respect for the limitations of even the best calculations. All too often my measurements differed enough from expectations to provide new insights into the physics or engineering that were missing from computational models.

As one example, I participated in many of the early laser fusion experiments. There was immense optimism then, based on the best calculations available at the time, that modestly sized, fairly inexpensive lasers would provide enough energy to ignite fuel and enable efficient production of fusion energy. In 1972, several researchers wrote "One kilo Joule of laser energy may be sufficient to generate an equal thermonuclear energy." Based on such assertions, some assumed that laser fusion would soon be producing power for the grid.

Thirty years later, you don't hear much today about laser fusion supplying grid power in the near future. The early predictions for success with small lasers are now replaced by construction of multi-megajoule, multibillion dollar facilities, where ignition and energy gain might be demonstrated.

So what went wrong? It seems that careful experiment, some done by my group at Los Alamos, simply did not support the optimism of the early calculations, which were sadly lacking in accurate descriptions of many aspects of the underlying physics. As these new facilities come into operation, we'll see if nature has more new physics surprises to reveal!

Calculations and modeling have a critical role in any technically complex endeavor. But I've learned that computational models are as good, or as bad, as the depth of the physics and engineering underpinning them. Models require careful validation and the Halden Program has been instrumental in validating many of our current codes.

In addition, I'm no stranger to international cooperation. During my time at Los Alamos, I was involved in international cooperative research when I served on and later chaired the NATO research study group on radiation effects. I hosted international scientists for extended stays in my Los Alamos group, and I spent five months in France in support of that international work.

With that as my background, I hope you understand why my interest in the work at the Halden project follows from my own personal experiences. And also you can appreciate that I was very glad to learn that the NRC has fostered and supported international cooperation, including significant participation in multinational research efforts.

Led by the NRC's Office of Nuclear Regulatory Research, our international cooperative research program covers a wide range of activities and technical disciplines: mixed oxide and high burn-up fuel, plant aging and material degradation, digital instrumentation and control, thermal-hydraulic and severe accident analysis, probabilistic risk assessment, fire risk, radiation protection, human performance, seismic risk, spent fuel, and waste management. Through these interests, we participate in major experimental programs using test facilities that are not available in the U.S. Access to these facilities expands our knowledge base, efficiently addresses research on high priority safety issues, and helps strengthen international cooperation that in turn strengthens oversight programs around the world

Data from these programs are used to develop new analytical models and updates for NRC's analytical codes and to validate existing models. International cooperative research programs also provide access to operating experience from foreign reactors, which augments our own programs in areas such as fire risk, plant aging and materials degradation, and pressurized thermal shock. Analysis of this experience contributes to our knowledge base and improved assessments of plant risk and to the development of risk-informed approaches to regulation.

In addition, as our senior staff retires and we hire less-experienced replacements, knowledge management will become a significant issue. International data bases, such as that associated with the work in the Halden Reactor Program, will be one of the key ways of transferring knowledge to these new workers.

Our Research Office has 95 bilateral and multilateral cooperative research agreements and seven more under negotiation with many international organizations. Through our participation in these international activities, we have the opportunity to exchange information with counterparts on regulatory activities, research results, and operating experience; to participate in peer reviews of regulatory programs and international safety standards and guidance, and to contribute to the outcome of emerging international issues.

Our international arrangements began prior to creation of the NRC. During 1974, the about-to-be-abolished Atomic Energy Commission negotiated and signed the first technical information exchange arrangements with Japan, France, Spain, Sweden and Switzerland. Later, these agreements transitioned to the NRC and were soon followed by arrangements with the United Kingdom, Italy, and Germany.

Today, those original eight "standard" arrangements have been augmented by 22 for a total of 30. We also have other arrangements, which are tailored to specific circumstances, generally reflecting more limited cooperation. These arrangements have led to more than 300 international assignees to the NRC. Their knowledge has informed the NRC, and as each returned to their national regulatory organizations they were able to share knowledge they gained during their stay with us.

The Halden Program is an essential component of our international cooperative research program. Over the years, there have been many positive contributions to the NRC from this program. For today's talk, I'll break these contributions into five different areas: Fuels, Materials and Water Chemistry, Instrumentation and Control, Human Factors, and Human Reliability.

Fuels

In the fuels area, let me note a recent (2004) Licensing Board hearing on the use of mixed-oxide (MOX) Lead Test Assemblies in a U.S. reactor. The NRC staff used fuel centerline thermocouple data from MOX tests in the Halden Reactor to support the hearing record.

We made further use of this and other Halden data to confirm analysis of the performance of the MOX Lead Test Assemblies and to support the use of the NRC fuel performance code FRAPCON-3 for MOX. Because of the availability of these valuable data, the use of MOX assemblies was approved and they are now in their first cycle of operation. In the report on the FRAPCON-3 code the staff noted that:

> *The current report is . . . noteworthy because of its extensive use of experimental data from test reactor programs (particularly the Halden Reactor Project . . .).*

The continued availability of fuel behavior data from Halden will be important inputs to the NRC staff's review of advanced fuel designs and new versions of computer codes submitted by fuel vendors.

Testing facilities with broad capabilities is a cornerstone of the Halden Project. In the fuels area, these facilities include the instrumented reactor, which I visited yesterday, the on-site gamma-scanning device, and the off-site hot cells. Additionally, the multiple loops and their in-reactor flasks have provided valuable data on cladding corrosion, cladding creep, and fission gas flow. Over the years the balance between steady-state and transient tests seems about right, although the NRC continues to primarily be interested in transient and accident behavior.

Looking toward the future in the fuels area, we expect Halden fission gas release and integral burnable poison data to address the issue of fuel performance limitations (e.g., end-of-life rod pressure limits). Also, the ongoing in-reactor LOCA test series will complement related hot cell tests in the United States and other countries by focusing on in-reactor effects that are different from those obtained in out-of-reactor tests. These data are of particular interest to NRC as we revise our cladding embrittlement regulatory criteria.

Materials and Water Chemistry

Turning to the materials and water chemistry area, for about a decade, material test specimens have been irradiated in the Halden reactor to levels typical of the end-of-life condition for BWRs. These specimens were then further tested in a U.S. laboratory to study several mechanical properties as a function of specific compositional influences or thermal treatment processes. These tests included examination of cracking susceptibility under slow tensile strain rates, fracture toughness, and crack growth rate determination. Subsequent evaluations of these specimens are now being carried out in simulated BWR environments to further validate our understanding of environmentally assisted degradation of reactor core internals, primary loop components and piping. The results of such tests are often used in our evaluation of stress-corrosion cracking events of core components and in determining the adequacy of aging management strategies as part of the license renewal process in the United States. For example, Halden tests will be used to verify the stress-corrosion cracking mitigation effectiveness of BWR hydrogen water chemistry. We are also making use of the crack-growth-rate data in understanding the effects of PWR coolant chemistry on materials, and look forward to receipt of additional data as it is developed.

Finally, we continue to encourage the recent Halden initiative to fabricate and evaluate in-core sensors for electrochemical potential and coolant electrical conductivity, as well as palladium electrode development for potential use in evaluations of BWR core internals. We are also interested in the development of electrochemical impedance spectroscopy instrumentation and calibration procedures for monitoring the oxidation of Zircaloy cladding on fuel elements.

Instrumentation and Controls

The area of instrumentation and control is evolving rapidly. Nuclear facilities have started to replace older analog systems and equipment with digital systems and equipment as analog replacement parts become more difficult to obtain and because digital systems offer the potential for better performance and flexibility.

However, there are obvious challenges associated with introduction of this technology into safety systems at nuclear facilities. These challenges include increased complexity, rapidly changing technology, new failure modes, reliability metrics, and consistently updating acceptance criteria and review procedures.

In response to these issues, the Halden Project has expanded its research efforts in the area of digital system safety. This expansion is providing a growing technical basis for more realistic safety decisions in this arena. This work also includes developing surveillance and monitoring techniques based on advanced decision algorithms, particularly in the areas of on-line monitoring and diagnostics. I understand that Halden-developed systems, such as core monitoring, condition monitoring of electrical cables, early fault detection, optimization of plant performance and maintenance, and computerized procedures, are of interest to some of our licensees for implementation in U.S. plants.

The NRC remains very interested in the Halden software engineering laboratory capability to support research, development, assessment, and training related to safety-system software engineering. For regulatory issues involving digital safety system requirements engineering, architecture, fault tolerance, reliability, pre-developed software tools and integrated tool environments, and objective acceptance criteria, the products generated by Halden will continue to aid the NRC in establishing the technical bases guiding our review of current and new digital system designs and technologies. Furthermore, these products will likely provide valuable input into advanced control room designs.

Finally, I'm very pleased that Halden is working with the Nuclear Energy Agency to develop a new database, Computer Systems Important to Safety, or COMPSIS, to collect digital system failure information to support improved operation and regulation of digital systems. This is an area in which improvement in our understanding of digital system failure modes and frequencies can greatly benefit from a worldwide data gathering effort.

Human Factors

In the area of human factors, your experiments related to human error, human performance, teamwork and the effects of computer-driven interfaces on human performance have been valuable to the NRC for development of review guidelines. We don't have a reconfigurable simulator for research use in the U.S., so access to Halden's HAMMLAB facilities is invaluable to us. A simulator that can be driven by either a PWR or BWR model, a prototype reconfigurable advanced control room with an integrated surveillance and control system, data collection facilities, and capabilities in virtual and augmented environments is a unique resource operated by a staff of knowledgeable and dedicated researchers.

We have used the results of Halden human factors research as part of the technical basis for regulatory guidance in areas such as alarm systems, control room design, display navigation, and development of human performance measures. The results have also been used as one of the bases for our Standard Review Plan. These guidance documents are for use in reviewing changes to control stations at current reactors, for licensing reviews of new reactors, for license amendment requests, and for plant inspections.

The related human reliability work to investigate the effects of context, task complexity factors, sustained workload and work practices in computer-based control rooms and team cooperation in new operational settings will also provide continuing contributions to the technical basis for human factors guidance. This will be especially important for new reactor designs and will supplement the NRC's Human Reliability Analysis efforts. The plans to address human system interfaces that deliver relevant data and information in comprehensible and understandable formats, and present the data and information in a manner that does not cause mental overload or confusion, will be useful for developing guidance for new advanced control rooms.

In addition, the Halden research in virtual environments is an application of exciting new technologies to support human-factors-design input into control room configurations, into radiation (and possibly fire) visualization methods, and into virtual reality-based team training.

Human Reliability

Finally let me turn to the area of human reliability. In the United States, the NRC has adopted a risk-informed approach to regulatory decision-making. Given the increasing importance of this approach, it is crucial to use Human Reliability Analysis or HRA methods, tools, and data that can adequately assess the human contribution to risk. The quality of HRA data available is an area that needs to be addressed. Because of its long history in performing studies on human factors, Halden has the capability, facilities, and expertise to conduct simulator experiments and collect data that can be applied to HRA modeling and quantification issues.

Experimental work at Halden can generate the data needed to improve HRA in terms of underlying theories and models. In addition, work at Halden helps to provide probability estimations of human errors during events and accidents. For example, performance shaping factors can be manipulated to collect data for measuring the effects of these factors on an operator's ability to successfully mitigate accidents. Halden results provide evidence of a high degree of successful operator performance as well as a lower degree of less optimal behavior and provide indications of the relative likelihood of success or failure to help explain factors contributing to both outcomes. Therefore, the results could be used to improve plant safety by identifying potential "vulnerabilities" in specific crew behaviors or potential "good practices" to be emphasized.

We encourage the Halden Program to continue the current line of research, further investigating the influence of various factors such as "task complexity" and the contribution of different "crew characteristics" to crew success or failure by addressing issues related to important accident sequences.

I was also interested to learn that we use the Halden-developed Picasso system to aid in the design of graphical user interfaces to improve training at our Technical Training Center. In fact, the Training Center's Nuclear Engineering Workstation Simulator, a classroom training tool originally developed with Halden assistance, continues to be used during training of NRC staff and has been recently upgraded by NRC personnel using the latest version of Picasso.

Halden is working with the U.S. Electric Power Research Institute, the Callaway Plant, and the Nuclear Engineering Department at the University of Illinois on a case study involving application of the Halden Virtual Reality system - CREATE - to develop a Callaway Plant virtual control room model for modernization of the Callaway main control room.

In closing, I want to note the great interest of the Commission in developing a multinational cooperative approach to design approvals for new reactors. Our Chairman discussed this Multinational Design Approval Program, or MDAP, at the recent General Assembly of the IAEA. Like the Halden Program, it would draw upon and benefit from multinational cooperation. Current global trends point toward construction of reactors in countries other than the country in which the reactor was first designed, certified, and operated. The NRC supports cooperation among the regulatory bodies of the relevant countries to facilitate the convergence of safety standards for new designs and improve the effectiveness and efficiency of associated regulatory reviews, safety analyses, and related programs.

Such a program should help improve the clarity and transparency of nuclear safety regulation across international borders and help to ensure that safe, carefully evaluated designs are being used to construct new nuclear power plants around the world.

Above all, the goal of international cooperation, whether in the Halden Program or in a future Multinational Design Approval Program, should be to assure safe operation of nuclear plants, both existing plants and new ones on the drawing boards. International cooperation is one of the best ways to assure that the knowledge base and experience in each country is augmented by that of our colleagues in other nations.

Public confidence in the safety of nuclear power and public confidence in nuclear regulators is vital in every nation that uses this energy source. Through international cooperation, we can strengthen our ability to maintain that confidence.