ELECTRIC POWER
RESEARCH INSTITUTE

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Kevin Witt
Project Manager
Japan Lessons Learned Project Directorate
Office of Nuclear Reactor Regulation
US Nuclear Regulatory Commission
Washington, DC 20555

Subject: EPRI Activities in Spent Fuel Pool Hazards Evaluation

Dear Mr. Witt:

Attached is a summary of EPRI activities and international coordination related to spent fuel pool hazards assessment and analysis and spent fuel storage, as requested.

Please let me know if you have any questions.

Sincerely,

Keith Waldrop
Senior Project Manager

Attachment

CHARLOTTE OFFICE
1300 West W.T. Harris Boulevard, Charlotte, NC 28262-8550 USA • 704.595.2000 • Fax 704.595.2860
Customer Service 800.313.3774 • www.epri.com

EPRI Activities and International Coordination Related to Spent Fuel Pool Hazard Assessment and Analysis

EPRI is an international organization that has engagement with 80% of the worlds' nuclear operators and receives 40% of its funding for nuclear R&D from non-US members. As such, the EPRI activities discussed in the following summary are used by (and informed by) the experiences and needs of EPRI's global membership.

Research related to the safe operation, monitoring and analysis of spent fuel pool (SFP) behavior includes probabilistic risk assessment, improved modeling of phenomena during abnormal and accident conditions, nondestructive evaluation of SFP steel liners and concrete walls, and activities that support safe, integrated management of used fuel at nuclear plant sites. These efforts also serve to address considerations raised both in the United States and internationally in the aftermath of Fukushima.

Early Event Analysis of Fukushima Spent Fuel Pools

In May 2012, EPRI released a report documenting a number of assessments of the Fukushima Daiichi spent fuel pools developed early in the response phase following the March 11, 2011 earthquake and tsunami (EPRI report 1025058). The analysis addressed many of the theories proposed in the months following the Unit 4 explosion, including scenarios in which spent fuel pools filled with water could generate large amounts of combustible hydrogen gas in a short time. EPRI's evaluations pointed away from the Unit 4 spent fuel pool as a cause of the damage to the Unit 4 reactor building. This result was corroborated and eventually confirmed by subsequent TEPCO inspections.

- *Summary of EPRI's Early Event Analysis of the Fukushima Dai-ichi Spent Fuel Pools Following the March 11, 2011 Earthquake and Tsunami*. EPRI, Palo Alto, CA: 2012. 1025058.

Probabilistic Risk Assessment Model Development

With respect to probabilistic risk assessment (PRA), EPRI has developed a generic methodology to guide the PRA practionner in modeling plant-specific interactions between SFP and reactor systems following internal initiators or seismic or fire initiators. The generic methodology identifies the various considerations that should be accounted for in modeling the plant-specific event sequences and has been tested by applying it to a pilot BWR plant. The methodology as well as the pilot applications are described in EPRI report 3002000498, published in 2013.

A similar approach was developed for PWRs in 2013, and a companion report was recently published (EPRI report 3002002691). The PWR methodology differs somewhat from the BWR

methodology for MARK I and II containment designs because the SFP is typically located in a separate fuel building. Described in report 3002002691 is the application of the methodology to a typical PWR design (with sub atmospheric containment design). This pilot study provided valuable insights in current operator procedures/guidance (EOP and SAMG) and piping alignments that are also documented in the report.

In addition to these two reports, EPRI published in 2013 a report compiling the current knowledge on SFP accident characteristics and SFP design considerations (EPRI report 3002000499). This reference document includes a description of the various safety functions related to SFPs (cooling, make up, spray, etc), the key support systems on which they rely, the major threats to these systems, and the potential evolution of accident sequences following internal initiators or external events initiators.

- *Spent Fuel Pool Risk Assessment Integration Framework (Mark I and II BWRs) and Pilot Plant Application*. EPRI, Palo Alto, CA: 2013. 3002000498.
- *PWR Spent Fuel Pool Risk Assessment Integration Framework and Pilot Plant* EPRI, Palo Alto, CA: 2014. 3002002691,
- *Spent Fuel Pool Accident Characteristics.* EPRI, Palo Alto, CA: 2013. 3002000499.

Deterministic Severe Accident Analysis Code Enhancement and Benchmarking

Lessons learned from Fukushima and from the PRA efforts have been incorporated into the development of deterministic models for SFP safety analysis through EPRI's Modular Accident Analysis Program (MAAP) code. The MAAP code is used globally by utilities and others to analyze plant transients and severe accident phenomena.[1] New and enhanced SFP models include more detailed modeling of spent fuel racks to account for inhomogeneous fuel distributions, heat transfer under degraded conditions, radiation heat transfer between racks, zirconium-air oxidation, and fuel relocation. These major enhancements have been incorporated into subsequent releases of MAAP5 in 2013, and future enhancements to MAAP are envisioned based on continuing benchmarking and feedback from international users.

EPRI Participation in OECD/NEA SFP Project[2]

In 2012, EPRI worked with NRC to participate in an international experimental program administered by the OECD/NEA. That work program was focused on ignition tests on prototypic fuel assemblies under conditions of oxidation in air to: validate severe accident codes for whole pool LOCA; investigate runaway Zr oxidation phenomena at scale; and develop improved fuel

[1] MAAP is licensed to organizations in 17 countries.

[2] Full title of OECD/NEA project: "An Experimental Program and Related Analyses for the Characterization of Hydraulic and Ignition Phenomena of Prototypic Water Reactor Fuel Assemblies"

pool source terms for severe accident consequence analysis. Under the terms of an addendum to the NRC – EPRI Memorandum of Understanding, EPRI obtained data from the OECD/NEA project to support benchmarking of its MAAP and GOTHIC codes.

Non-Destructive Evaluation (NDE) Technologies and Methods

Concerns about potential degradation of the welds used in fuel pools and fuel pool transfer canal liners have prompted an EPRI research effort to evaluate the viability of various nondestructive evaluation tools and techniques. Candidate techniques include alternating current field measurement (ACFM) and eddy current (EC). ACFM sensors were evaluated for their ability to operate under irradiated conditions along with potential delivery systems tailored for service in the SFP environment. The EC technique is available for ground flush weld application such as plug welds and can be deployed in non-irradiated conditions both dry and underwater. Results of NDE investigation and sampling of best practices for PWR spent fuel pool leaks can be found in EPRI reports 1025214 and 1021147. EPRI continues to track SFP and transfer canal liner issues and is considering future activities to support inspection, repair, and mitigation.

EPRI is also examining potential SFP integrity issues related to boric acid attack on concrete substructures. This multi-year effort will conduct a range of laboratory and simulation experiments on aggregate reactivity, cement paste leaching, concrete leaching, and chemical transport to advance the understanding of boric acid attack on concrete. Fundamental laboratory experiments completed in 2013 are being followed by corrosion experiments in 2014 using steel embedded in cement paste to more closely represent field conditions. A final report will be issued in 2015.

- *Nondestructive Evaluation: Addressing Groundwater Contamination Issues to Identify Suitable NDE Technologies and Repair Methods for Spent-Fuel Pool Liner Leaks*. EPRI, Palo Alto, CA: 2010. 1021147.
- *Advanced Electromagnetic Inspection Methods for Fuel Pool and Transfer Canal Liners*. EPRI, Palo Alto, CA: 2012. 1025214.

Integrated Used Fuel Management

EPRI's Used Fuel and High-Level Waste Management program addresses technical issues affecting integrated management of used fuel at plant sites among members from 7 countries and 4 continents. EPRI's R&D in used fuel management focuses on used fuel storage, handling and transportation. The current absence of ultimate geologic disposal sites for used fuel and high-level waste compels nuclear plant owners to store this material on-site until such facilities are available. In some countries, plants have already begun moving used fuel into dry storage and may be required to store used fuel far longer than originally envisioned. During these

extended periods of storage, stakeholders need confidence that the safety functions of storage and transportation are maintained. EPRI research is assessing the technical factors involved in ensuring safe extended storage, including storage system and fuel integrity; the technical issues associated with transportation of used fuel, particularly the mechanical behavior of high burnup used fuel; and the technical issues that may arise relative to regulations impacting used fuel and high-level waste handling. Priorities include: the planning and execution of a high burnup dry storage used fuel demonstration project; identifying key failure modes and effects for dry storage systems (including chloride-induced stress corrosion cracking); development of an aging management plan for dry storage systems; in-service dry storage system inspection campaigns and method/tool development; and the development of nondestructive evaluation techniques for stainless steel canisters used for dry storage. In 2013, EPRI was awarded a contract from the U.S. Department of Energy for a high burnup used fuel research and development project. The project will provide confirmatory data from actual storage conditions that laboratory experiments and models projecting storage system behavior reflect can use as benchmarks to better understand the behavior of high burnup fuel. This work will be initiated at a volunteer utility site and will take on the order of 15 years to complete.

EPRI is also sponsoring a number of R&D activities that support criticality analyses and understanding of performance, integrity, and potential degradation of neutron absorber materials. A high priority for EPRI has been the development of benchmarking information to address uncertainties in criticality calculations for used fuel storage in pools. In the area of neutron absorbers, EPRI draws upon industry experience from users and manufacturers to maintain a handbook on material properties, manufacturing processes, and field application to enable more efficient management of neutron absorber materials and guide development of improved materials.

Extended Storage Collaboration Program (ESCP)

EPRI leads a broad group of organizations through the Extended Storage Collaboration Program (ESCP) to investigate aging effects and mitigation options for the extended storage and transportation of used nuclear fuel and high level waste (HLW). ESCP grown to over 175 members representing nearly 70 industry, governmental, regulatory and academic organizations from approximately 20 countries. Close coordination with related IAEA activities has been successfully accomplished, and coordination with the OECD Nuclear Energy Agency effort in this area is underway. Through ESCP, participants have been able to share information, coordinate planning, and to individually or jointly fund high priority R&D in order to close the technical gaps for addressing extended storage issues.

Selected EPRI Reports Related to Storage of Used Fuel

- Literature Review of Environmental Conditions and Chloride-Induced Degradation Relevant to Stainless Steel Canisters in Dry Cask Storage Systems. EPRI, Palo Alto, CA: 2014. 3002002528.
- Calvert Cliffs Stainless Steel Dry Storage Canister Inspection. EPRI, Palo Alto, CA: 2014. 1025209.
- PWR Fuel Reactivity Depletion Verification Using Flux Map Data. EPRI, Palo Alto, CA: 2014. 3002001948.
- End-of-Life Rod Internal Pressures in Spent Pressurized Water Reactor Fuel. EPRI, Palo Alto, CA: 2013. 3002001949.
- Failure Modes and Effects Analysis (FMEA) of Welded Stainless Steel Canisters for Dry Cask Storage Systems. EPRI, Palo Alto, CA: 2013. 3002000815.
- Depletion Reactivity Benchmark for the International Handbook of Evaluated Reactor Physics Benchmark Experiments. EPRI, Palo Alto, CA: 2013. 3002000306.
- *Impacts Associated with Transfer of Spent Nuclear Fuel from Spent Fuel Storage Pools to Dry Storage After Five Years of Cooling, Revision 1*. EPRI, Palo Alto, CA: 2012. 1025206.
- *Cost Impact of Using ISG-8 Rev. 3 for PWR Spent Fuel Pool Criticality Analysis*. EPRI, Palo Alto, CA: 2012. 1026483.
- *Extended Storage Collaboration Program International Subcommittee Report*. EPRI, Palo Alto, CA: 2012. 1026481.
- *Strategy for Managing the Long Term Use of BORAL® in Spent Fuel Storage Pools*. EPRI, Palo Alto, CA: 2012. 1025204.
- *Summary of EPRI's Early Event Analysis of the Fukushima Dai-ichi Spent Fuel Pools Following the March 11, 2011 Earthquake and Tsunami*. EPRI, Palo Alto, CA: 2012. 1025058.
- *Utilization of the EPRI Depletion Benchmarks for Burnup Credit Validation*. EPRI, Palo Alto, CA: 2012. 1025203.
- *Extended Storage Collaboration Program (ESCP)*. EPRI, Palo Alto, CA: 2011. 1022914.
- *Benchmarks for Quantifying Fuel Reactivity Depletion Uncertainty*. EPRI, Palo Alto, CA: 2011. 1022909.
- *Delayed Hydride Cracking Considerations Relevant to Spent Nuclear Fuel Storage*. EPRI, Palo Alto, CA: 2011. 1022921.
- Impacts Associated with Transfer of Spent Nuclear Fuel from Spent Fuel Storage Pools to Dry Storage After Five Years of Cooling. EPRI, Palo Alto, CA: 2010. 1021049.
- *Industry Spent Fuel Storage Handbook. EPRI, Palo Alto, CA: 2010*. 1021048.

- *Used Fuel and High-Level Radioactive Waste Extended Storage Collaboration Program*. EPRI, Palo Alto, CA: 2010. 1020780.
- *Handbook of Neutron Absorber Materials for Spent Nuclear Fuel Transportation and Storage Applications*. EPRI, Palo Alto, CA: 2009. 1019110.
- *Cost Estimate for an Away-From-Reactor Generic Interim Spent Fuel Storage Facility*. EPRI, Palo Alto, CA: 2009. 1018722.
- *Climatic Corrosion Considerations for Independent Spent Fuel Storage Installations in Marine Environments*. EPRI, Palo Alto, CA: 2006. 1013524.
- *Effects of Marine Environments on Stress Corrosion Cracking of Austenitic Stainless Steels*. EPRI, Palo Alto, CA: 2005. 1011820.
- *Probabilistic Risk Assessment (PRA) of Bolted Storage Casks: Updated Quantification and Analysis Report*. EPRI, Palo Alto, CA: 2004. 1009691.
- *Technical Bases for Extended Dry Storage of Spent Nuclear Fuel*. EPRI, Palo Alto, CA: 2002. 1003416.
- *Dry Cask Storage Characterization Project*. EPRI, Palo Alto, CA: 2002. 1002882.
- *Creep as the Limiting Mechanism for Spent Fuel Dry Storage*. EPRI, Palo Alto, CA: 2000. 1001207.
- *The Castor-V/21 PWR Spent-Fuel Storage Cask: Testing and Analyses*. EPRI, Palo Alto, CA: 1985. NP-4887.

<u>Selected EPRI Reports Related to Transportation of Used Fuel</u>

- *Resolution of Spent-Fuel Transportation Issues*. EPRI, Palo Alto, CA: 2010. 1016637.
- *Criticality Risks during Transportation of Spent Fuel Pool – Revision 1*. EPRI, Palo Alto, CA: 2008. 1016635.
- *Fuel Relocation Effects for Transportation Packages*. EPRI, Palo Alto, CA: 2007. 1015050.
- *Spent-fuel Transportation Applications – Normal Conditions of Transport*. EPRI, Palo Alto, CA: 2007. 1015049.
- *Spent Fuel Transportation Applications – Assessment of Cladding Performance*. EPRI, Palo Alto, CA: 2007. 1015048
- *Assessment of Accident Risk for Transport of Spent Nuclear Fuel to Yucca Mountain Using RADTRAN 5.5*. EPRI, Palo Alto, CA: 2006. 1013450.
- *Summary of the NAS Report, "Going the Distance? The Safe Transport of Spent Nuclear Fuel and High-Level Radioactive Waste in the United States" and EPRI's Comments*. EPRI, Palo Alto, CA: 2006. 1010075.
- *Spent Nuclear Fuel Transportation – An Overview*. EPRI, Palo Alto, CA: 2004. 1009226.