

Nuclear Research Trends Post-Fukushima

Prepared for:
Canadian Nuclear Safety Commission

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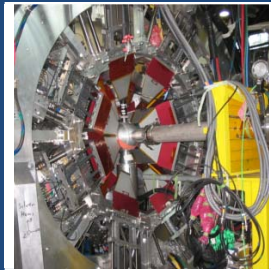


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1. Introduction

1.1 Background

The Canadian Nuclear Safety Commission (CNSC) directs an extramural research program to provide staff with independent scientific and technical knowledge in support of the CNSC's mission. To inform future research priorities, the CNSC is interested in understanding research trends sparked by the Fukushima incident. The events at the Fukushima Daiichi nuclear power plant on March 11, 2011 abruptly changed the nuclear landscape internationally. In a 'post-Fukushima' world, standard practices are being challenged and new questions are being asked. Although the CANDU design is fundamentally different from the reactors at Fukushima, there are still likely to be lessons that the CNSC can learn from the Japanese incident.

1.2 Study Objective

The CNSC required a review of the nuclear literature relating to analysis and research post-Fukushima to identify new research or research trends that have emerged in response to the Japanese incident.

1.3 Study Approach

The study was undertaken employing two main lines of inquiry, interviews and document and literature review, using the interviews to provide guidance to the direction and scope of the literature review. A framework for the study findings as set out below was developed that organized the data by sponsoring organization and by three categories: (i) Fukushima-related research needs/themes identified by organization; (ii) Resulting research projects planned or underway; and (iii) Resulting research projects completed and published. For each category, the data was then linked as far as possible to the following CNSC research disciplines: Fitness for Service; Safety Analysis; Physical Design; Waste Safety; Environmental Protection/Environmental Risk Assessment; Radiation Protection; Human Performance Management and Human Factors; Safeguards; Emergency Planning; and Social Aspects. A description of these disciplines is provided in Appendix A.

Interviews: Interviews were conducted with representatives from the nuclear regulatory agencies of the US, France, the UK, and Japan and also with representatives from the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD), the International Atomic Energy Agency (IAEA) and the Electric Power Research Institute (EPRI). The selection of and contact with interviewees from these organizations was facilitated by the Research Project Officer and the International Relations Division of the CNSC. A list of interviewees is given in Appendix B.

Literature Review: The literature review examined documents and articles from a wide range of web sites identified in discussions with the Project and Technical Authorities and the international interviewees (all data sources are listed in Appendix C including those that are referenced as footnotes in Appendices D,E and F).

1.4 Study Challenges

The main challenges for the study were to reach interviewees in the original time frame of the study, to obtain research plans post-Fukushima from national and international agencies as well as publications of completed research, to obtain information on completed research projects and to link the international research being conducted to the CNSC research disciplines. To address the first challenge, the project time was extended to allow for the interviews. The second challenge posed a difficulty for the study because agencies are still in the process of developing the plans for their longer range research. It is expected for example that both the US and the UK will be publishing their plans in 2013. In place of published plans, we relied on the national presentations to the Annual Regulatory Information Conferences (RIC) in 2012 and 2013 for an indication of main research interests. This was supplemented by the information we obtained through interviews and correspondence with representatives of the nuclear regulatory agencies.

The third challenge involved efficiently finding enough published literature on completed post-Fukushima research projects from sources like the IAEA's International Nuclear Information System (INIS). The CNSC's library staff provided assistance to prepare a modest list of completed research projects recognizing that much of the relevant research is still underway or in the planning stage. For the fourth challenge, this study has undertaken to link the CNSC disciplines to the post-Fukushima research but a more in-depth look at the connections will be needed by the CNSC to fully understand how the CNSC can fully benefit from this international research. Also, the methodology for analyzing the information collected on research issues and projects to identify common trends and patterns involved a combination of counts of the occurrence of subject areas and judgement about the assignment of subject areas to specific groupings due to variations in terminology used. The resulting analysis provides an approximation of the ranking of the groupings of research subject areas but this is considered sufficient to show the overall emerging patterns and trends.

2. Summary Findings

2.1 Research Interests

The following table provides the results of an analysis of research interests identified from documents and interviews with key informants from international nuclear research organizations. They are grouped in common subject matter categories and listed in the order of the approximate frequency of their occurrence. Details on these research interests are given in Appendix D.

Main Research Interests Subject Categories	Frequency (approx.)
Emergency Planning	21
Hydrogen, Containment Structure, Vents	14
Severe Accident Management Guidelines	11
Seismic, Earthquakes ,Tsunami, Flooding	8
Station Blackout, Emergency Power	7
Safety/Risk Evaluation/Review/Assessment/Management	7
Spent Fuel Pools/Storage	6
Iodine/Iodide/Radiation	5
Overall Assessment/Simulation of Accident	4
Instrumentation	2
Heat Sinks	2
Human Resources	2
Regulatory Infrastructure	1
Safety Culture	1
Crisis Communications	1

The research interests identified were also cross-tabulated against the 10 categories of research disciplines commonly used by the CNSC (Appendix A). The following table shows the results of this analysis.

Research Interests Subject Correspondence To CNSC Research Disciplines	Frequency (approx.)
Physical Design	44*
Safety Analysis	39*
Emergency Planning	18*
Environmental Protection/Environmental Risk Assessment	9
Human Performance Management and Human Factors	6
Radiation Protection	4
Social Aspects	2

*A further breakdown of the specific subject areas in the top three CNSC research disciplines (marked with an asterix in the above table) are provided below.

Main Research Interests Subjects Within Physical Design	Frequency (approx.)
Hydrogen, Containment Structure, Vents	13
Station Blackout, Emergency Power	7
Spent Fuel Pools/Storage	3
Instrumentation	2
Heat Sinks	2

Main Research Interests Subjects Within Safety Analysis	Frequency (approx.)
Safety/Risk Evaluation/Review/Assessment	9
Seismic, Earthquakes ,Tsunami, Flooding	9
Severe Accident Management Guidelines	7
Hydrogen, Containment Structure, Vents	3

Main Research Interests Subjects Within Emergency Planning	Frequency (approx.)
Emergency Response/Planning/Preparedness*	13
Iodine/Iodide/Radiation	3

*Emergency response planning subject areas largely involved the strengthening of operating procedures and severe accident management guidelines, and their related regulatory aspects. A small grouping dealt with radiological protection issues in emergency response planning. The remaining areas focused on particular administrative or technical subjects such as data systems capabilities, zone size, and subcontracting practices.

2.2 Research Projects Planned or Underway

The following table provides the results of an analysis of research projects that are planned or underway as identified from documents and interviews with key informants from international nuclear research organizations. They are grouped in common subject matter categories and listed in the order of the approximate frequency of their occurrence. Appendix E contains a detailed listing of the projects.

Main Planned or Underway Research Project Subject Categories	Frequency (approx.)
Hydrogen, Containment Structure, Vents	15
Seismic, Tsunami, Flooding	14
Severe Accident Management Guidelines	8
Spent Fuel Pools/Storage	7
Station Blackout, Emergency Power, Battery	7
Safety/Risk Evaluation/Review/Assessment	7
Electrical Power Supply/Grid	4
Overall Assessment/Simulation of Accident	4
Emergency Planning	4
Instrumentation	2

Safety Culture	2
Iodine/Iodide/Radiation	1
Heat Sinks	1

The research projects identified were also cross-tabulated against the 10 categories of CNSC research disciplines. The following table shows the results of this analysis.

Research Project Subject Correspondence To CNSC Research Disciplines

Physical Design	58*
Safety Analysis	56*
Emergency Planning	9
Environmental Protection/Environmental Risk Assessment	9
Human Performance Management and Human Factors	8
Radiation Protection	2

*A further breakdown of the specific subject areas in the top two CNSC research disciplines (marked with an asterix in above table) are provided below.

Main Research Project Subjects Within Physical Design Frequency (approx.)

Hydrogen, Containment Structure, Vents	12
Station Blackout, Emergency Power	7
Spent Fuel Pools/Storage	7
Electrical Power Supply/Grid	4
Instrumentation	2
Heat Sinks	2

Main Research Project Subjects Within Safety Analysis Frequency (approx.)

Seismic, Earthquakes ,Tsunami, Flooding	16
Safety/Risk Evaluation/Review/Assessment	7

Severe Accident Measures/Guidelines	6
Hydrogen, Containment Structure, Vents	5

2.3 Completed Research Projects

The following table provides the results of an analysis of research projects identified from documents and interviews with key informants from international nuclear research organizations as well as a search of published research literature that have been completed and published. They have been grouped in common subject matter categories and listed in the order of the approximate frequency of their occurrence. Appendix F contains a detailed listing of the projects and Appendix G indicates where the research was done to the extent we were able to determine.

Main Completed Research Project Subjects	Frequency (approx.)
Overall Assessment/Simulation of Accident	7
Assessment/Mitigation of Radiological Releases	6
Nuclear Policy	4
Relevant Past Research	2
Health Risk Assessment	1
Public Perception of Risk	1

The completed research projects identified were also cross-tabulated against the 10 categories of research disciplines commonly used by the CNSC. The following table shows the results of this analysis.

Completed Research Project Subject Correspondence To CNSC Research Disciplines	
Safety Analysis	11
Environmental Protection/Environmental Risk Assessment	11
Physical Design	10
Radiation Protection	9
Emergency Planning	8
Social Aspects	8
Human Performance Management and Human Factors	3

3. Conclusions

1. The Fukushima nuclear accident has prompted an immense amount of technical analysis among many nuclear regulatory and research organizations to assess nuclear plant safety, emergency preparedness, and the need for physical and procedural modifications. This focus on shorter term concerns is shown in the analysis of the completed and published research projects, where the main subject matter involved overall assessments or simulations of the accident and the resulting radiological releases. Almost half of these projects were undertaken by non-profit organizations such as the Electric Power Research Institute. The remainder of the projects were conducted in approximately equal parts by government agencies, universities, international organizations and the private sector.
2. The staged response of the US Nuclear Regulatory Commission (NRC) to the Fukushima accident, that is to create a three tiered timetable, is indicative of how most regulatory agencies seem to be reacting: Tier 1 - immediate implementation; Tier 2 – resource or critical skill set limitations to implementation; Tier 3 – further study and research to support regulatory action. Longer term research built on longer term research plans will take time to develop as we found in the case of the UK Office for Nuclear Regulation (ONR) and the NRC who are not expected to publish their research plans until later this year.
3. Despite the lack of research plans, we believe that the linkages we have been able to identify between current research interests and ongoing Fukushima-related research and CNSC’s research disciplines provide helpful evidence in addressing the research questions posed for this study. The data presented indicate research priority areas, possibly reflecting more an acceleration of ongoing research rather than new research. The overwhelming majority of research needs identified and subsequent projects planned or already underway relate to the CNSC’s Physical Design, Safety Analysis and Emergency Planning research disciplines. These linkages are set out in Appendices D, E and F.
4. For Physical Design the following main subject areas were evident: Hydrogen, Containment Structure, Vents; Station Blackout, Emergency Power; Spent Fuel Pools/Storage; Instrumentation and Heat Sinks. The main subject areas falling under Safety Analysis included: Seismic, Earthquakes, Tsunami, Flooding; Safety/Risk Evaluation/Review/Assessment; Severe Accident Measures/Guidelines; and Hydrogen, Containment Structure, Vents. Finally, for Emergency Planning, the subject area of Emergency Response/Planning/Preparedness was the dominant theme with Iodine/Iodide/Radiation having a secondary role.

Appendix A

CNSC Research Disciplines

CNSC has described the most pertinent issues/challenges engaging the Research and Support Program by Research Discipline and in parallel with CNSC's regulatory framework as follows:

1. Fitness for Service

Due to the aging of CANDU reactors in Canada, much research is being done to ensure fitness for service for safe continued operation of the reactors. Research in this area is divided into the following sub-programs:

Aging Management: It is expected that all operators of nuclear reactors have an aging management program that deals with any aging issues that arise. Much research is being done internationally to feed into the development of requirements for these programs.

Equipment Fitness for Service/Equipment Performance: Requirements for in-service inspection of components are constantly being updated based on better understanding of degradation mechanisms. In addition, Fitness for Service Guidelines (FFSG) have been going through a revision, mainly at the request of industry, and the CNSC needs to continue conducting independent research to ensure that these change requests are valid.

Life Cycle Management: CNSC asks the licensees to develop and submit Life Cycle Management Programs (LCMP) to demonstrate their capabilities to manage and mitigate the aging related degradation mechanisms. As such, CNSC staff is required to ensure that these programs are adequate. Research in the Life Cycle Management area will concentrate on ensuring adequate knowledge and understanding of degradation mechanisms.

Structural Integrity: Testing is required to better understand the effects of material degradation on structural integrity of components.

2. Safety Analysis

Industry is reviewing their safety analysis methodology with the intent to prove that there are sufficient safety margins in their facilities to delay de-rating due to aging. CNSC staff is reviewing these methodologies to ensure that they are valid.

In addition, to provide the oversight necessary to prevent unreasonable risks to persons and the environment from nuclear or radiological activities as a result of potential external hazards and events, CNSC staff conducts research on different accident scenarios. Computational analysis is used to predict response of safety systems and structures.

Research is divided into the following sub-programs:

Deterministic Safety Analysis: Deterministic Safety Analysis focuses on conservative analysis of design basis accidents (normally internal events such as Loss of Coolant Accidents) using computer models that simulate accident behaviour and plant response as it progresses in time. The purpose is to demonstrate, with a high degree of confidence, that there is no (or only limited) damage to fuel and no significant release of radioactivity for any accident within the design basis.

Hazards Analysis: Hazard analysis focuses on assessment of the plant response to external events (such as earthquake or fire). The emphasis is on demonstrating that at least one line of defence for each of the fundamental safety functions (control, cool and contain) is qualified to withstand the event.

Probabilistic Safety Analysis: PSA identifies all the plant components that are needed to mitigate any postulated event and their likelihood of failure. The overall probability of core damage or large release of radioactivity is calculated from the logic models.

Severe Accident Analysis: Severe accident analysis is similar to deterministic safety analysis except that the behaviour modelled is much more complex and uncertain. The main purposes are to identify ways of mitigating the accident (such as through limiting core damage or minimizing radioactive release) and to evaluate Severe Accident Management Guidelines which would be followed by operators in the event of a severe accident.

3. Physical Design

Research in Physical Design may cover several different engineering disciplines; however, it can be best captured in the following sub-programs:

Safety Engineering: Modern Safety Engineering is an evolving field with many new approaches and questions. Licensees are continually upgrading or enhancing approaches to design criteria. (eg. Post tensioning methodology of concrete, etc.)

Engineering Protection Against Malevolent Acts: Due to emerging threats around the world, the CNSC and the global community have taken a more serious look at protecting nuclear reactors from malevolent acts. Therefore, research is required to review the effect that these threats have on design requirements. These attacks can be either physical or technological in nature. For example, this includes establishing design requirements for resistance to aircraft crash.

New and Innovative Technologies: Several international vendors have presented new designs for the new generation of reactors and studies are underway to better understand the new designs and their safety features. The CNSC is also reviewing the current regulatory requirements to meet the needs of the new designs.

4. Waste Management

The Safety and Control Area (SCA) for Waste Management includes internal waste-related programs which form part of the facility's operations, waste processing and storage, and planning for decommissioning. The sub-programs are as follows:

Managing Mine Waste: This sub-program aims to address mining issues with particular Canadian interest, such as identifying the potential risks and consequences of managing mine waste in regions of Canada that have permafrost, as well as general best practices in mine waste management. In addition, the CNSC is interested in assessing the effectiveness of mitigation measures for mine waste by studying the factors controlling the long term behaviour of elements of concern in uranium mine waste (e.g radium).

Long-term management of nuclear waste: Increasingly, the nuclear community is discussing how best to manage nuclear waste for the long-term. The CNSC's role in this discussion is to evaluate long-term safety issues related to the disposal of radioactive wastes as well as harmonizing the review of safety cases with other countries for geological repositories and developing guidance documents.

5. Environmental Protection

The Safety and Control Area (SCA) for Environmental Protection includes programs that identify, control and monitor all releases of radioactive and hazardous substances and effects on the environment from facilities or as the result of licensed activities. The sub-programs are as follows:

Transport and Biological Effects of Contaminants in the Environment: The driver of this sub-program is to understand the fate, transport and biological effects of contaminants of concern in the environment, especially as these effects pertain to historically contaminated soils.

Biological Effects of Low-dose / Chronic Exposure to Alpha Radiation: The objective of this sub-program is to address low-dose, chronic-exposure, alpha radiation effects on fish, mammals and invertebrates in the laboratory and in the field.

Behaviour of Tritium in the Environment: This sub-program aims to understand the behaviour of Organically Bound Tritium in the environment.

6. Radiation Protection

The Safety and Control Area (SCA) for Radiation Protection includes programs that identify, control and monitor all sources of exposure to radiation from nuclear substances and effects on human health from facilities or as the result of licensed activities. Research is divided into the following sub-programs:

Operational Radiation Protection: The Information System on Occupational Exposure (ISOE) provides a forum for radiation protection professionals from nuclear utilities and national

regulatory authorities worldwide to share dose reduction information, operational experience and information to improve the optimization of radiological protection at Nuclear Power Plants (NPP). Participation in the ISOE allows Canada to benchmark the radiation protection performance of our NPPs with those in other countries and it provides international insight to ALARA initiatives and programs world-wide. All of this helps CNSC radiation protection specialists increase their ability to assess licensee Radiation Protection (RP) programs.

Dosimetry: This sub-program aims to fill gaps in understanding the behaviour of nuclear substances that are taken into the human body, either occupationally or by members of the public as a result of activities licensed by the CNSC. This sub-program also aims to validate current CNSC recommendations, requirements and expectations relating to methods to ascertain doses to workers and the public.

Health Effects: This sub-program aims to fill gaps in knowledge on the health effects in populations exposed to ionizing radiation from facilities or as a result of licensed activities. These knowledge gaps are filled by assessing risk and conducting disease surveillance of populations exposed to ionizing radiation from facilities or as a result of licensed activities, and by assessing the biological effects of ionizing radiation as it interacts with living tissue.

7. Human Performance Management

Experience has shown that human performance plays a major role in safety during the life cycle of nuclear installations, not only in operation, but also in design, construction, modification, emergency and decommissioning. Human performance is the outcome of human behaviours, functions and actions in a specified environment, reflecting the ability of workers and management to meet the system's defined performance, under the conditions in which the system will be employed. Human and organisational factors are now more and more considered as important for safety. Indeed, the nuclear community has to cope with a lot of challenges in the operation of existing plants and the design of new ones. These challenges, such as new technology, modernization programs, organisational changes, design of advanced reactors, changes in staff and competences, evolution of requirements and regulation, etc. all have an influence on how humans and organisations may work safely and manage all kinds of situations, including unanticipated ones.

Human & Organizational Factors (HOF) Regulatory Framework Development: Because nuclear safety faces changing requirements and challenges, a significant amount of research is needed to support the on-going development and improvement of the CNSC's HOF-related regulatory framework applicable to the full range of licensees.

Human Performance in NPP Emergency & Accident Response: With the introduction of advanced plants (both modernization of existing plants and new plants) comes new reactor and system designs, new tools to support plant personnel, and changes to nuclear power plant staffing configurations. The concepts of operation and maintenance for this new generation of plants are likely to be quite different from those employed in today's plants. It is important that the

potential impact of these developments is evaluated and understood in order to determine the acceptability of new designs to support human performance in maintaining plant safety.

Personnel Examination and Certification: The CNSC has limited experience with the development and design of written questions. Written questions, including multiple choice questions, are currently used in recertification testing for NPP staff and for certification of Exposure device operators. As licensees already use written questions, including multiple choice questions, this is a short-term requirement.

8. Safeguards and Non-Proliferation (Canadian Safeguards Support Program)

The mission of the Canadian Safeguards Support Program (CSSP) is to contribute to the fulfillment by the CNSC of Canada's international obligations with respect to safeguards – as laid out in the Canada-IAEA Safeguards Agreement and the Additional Protocol – and in particular to enhance the effectiveness and efficiency of the IAEA safeguards regime. The majority of the work is seen as medium urgency to provide cost savings to licensees, the CNSC and the IAEA. The work carried out by the CSSP has been divided into three sub-programs:

Safeguards equipment, techniques and training: In carrying out its safeguards activities, the IAEA makes use of specialized technology. This sub-program groups together challenges related to safeguards equipment, specialised techniques and associated training needs. This sub-program also encompasses the need for ongoing support of Canadian-developed safeguards equipment. CANDU facilities are currently equipped with safeguards instrumentation that has been developed and installed using CSSP assistance. These legacy systems will need periodic upgrading throughout their life cycles.

IAEA support for information-based safeguards: The IAEA has recently undergone a fundamental shift in how it thinks about safeguards, moving away from a rigid system based on prescriptive criteria towards one that is: more focused on areas of concern; adaptable to the changing environment; and objectives-based. This so-called “information-driven” approach to safeguards is already being applied in Canada, under Canada's State-level Integrated Safeguards Approach, and has led to significant increases in efficiency. However, the application of this approach presents challenges in terms of information management, in that large volumes of operational and accountancy data need to flow in near-real time from the licensee to the CNSC and the IAEA.

Safeguard concepts and innovation: In addition to its more tangible projects, the CSSP is also involved in the conceptualization of safeguards approaches. In that context, this sub-program focuses on knowledge gaps within the safeguards system that would benefit from further research and/or that require the development and testing of innovative concepts and ideas.

9. Emergency Planning

The definition of a nuclear emergency is established in CNSC Policy on Nuclear Emergency Management (P-325) as: “*any abnormal situation that may increase the risk of harm to the*

health and safety of persons, the environment, or national security, and that requires the immediate attention of the CNSC". It is an abnormal situation which requires action beyond the scope of normal procedures and additional resources/coordination are required to effectively respond to minimize the impact.

Emergency planning refers to the activities to prepare for, respond to, and recover from nuclear emergencies.

10. Social Aspects

The social side to the nuclear discussion is broad and not well defined. Typical topics include, but are not limited to, the public risk perception of nuclear power, policy approaches to nuclear power, community engagement and consultation, etc.

Appendix B

Organizations contacted that participated in the study

Organizations	Interviewees
US Nuclear Regulatory Commission (NRC)	Donna Marie Sangimino, International Programs Team, Team Leader; Rob Taylor, Deputy Director, Japan Lessons Learned Project Directorate; Kathy Gibson, Director of Safety Analysis Donna-Marie.Sangimino@nrc.gov
UK Office for Nuclear Regulation (ONR)	Dr Andy Hall, Deputy Chief Inspector of Nuclear Installations and Director of Regulatory Standards (written response) andy.hall@hse.gsi.gov.uk
Electric Power Research Institute (EPRI)	Ken Canavan, Director of Plant Technology and Brian Schimmoller, Marketing Communications Leader ken.canavan@epri.com
Japan Nuclear Regulation Authority (NRA)	Tadashi Yamada, Bilateral Cooperation, International Affairs (written response) tadashi.yamada@go.jp
L'Institut de Radioprotection et de Sûreté Nucléaire (IRSN)	Ahmad Cheikh-Ali, International Relations Coordinator (written response) Ahmad.cheikh-ali@irsn.fr

Organizations contacted but did not participate in the study

Organizations	Contact
Nuclear Energy Agency (NEA)	Javier Reig, Head of the NEA Nuclear Safety Division Javier.reig@oecd-nea.org
International Atomic Energy Agency (IAEA)	(no contact provided)

Appendix C

Listing of reviewed documents and articles

United Kingdom

Office of Nuclear Research (ONR) Nuclear Research Index 2012

- Civil Engineering
- External Hazards
- Human Factors
- Internal Hazards
- Plant modeling
- Probabilistic Safety

ONR Final Report on Fukushima

ONR Post-Fukushima Research

Japan

Japan Nuclear Energy Safety (JNES) Annual Report April 2011 - March 2012

Tokyo Electric Power Company Estimation of Radioactive Material Released to the Atmosphere during the Fukushima Daiichi NPS Accident May 2012

Nara Medical University: The disaster at Japan's Fukushima-Daiichi nuclear power plant after the March 11, 2011 earthquake and tsunami, and the resulting spread of radioisotope contamination.

(http://econpapers.repec.org/article/eesoceco/v_3a41_3ay_3a2012_3ai_3a4_3ap_3a360-363.htm)

Seinan Gakuin University Experience of technological and natural disasters and their impact on the perceived risk of nuclear accidents after the Fukushima nuclear disaster in Japan 2011: A cross-country analysis (<http://econpapers.repec.org/paper/pramprapa/37016.htm>)

Japan Atomic Energy Agency: Emergency response by robots to Fukushima-Daiichi accident: summary and lessons learned (<http://www.emeraldinsight.com/journals.htm?articleid=17047824>)

United States

Electric Power Research Institute (EPRI) Fukushima Task Force Report 2012

EPRI Fukushima Newsletter April 2012

EPRI Summary of EPRI Research Applicable to Nuclear Accident Scenarios, 1023403 Technical Update June 2011

EPRI Fukushima-Related Research Activities: An EPRI Progress Report 102582, August 2012

EPRI Investigation of Strategies for Mitigating Radiological Releases in Severe Accidents: BWR Mark I and Mark II Studies 2012 Technical Report

Nuclear Regulatory Commission (NRC) Fukushima Task Force Report SECY-11-0093 July 2011

NRC Fukushima Taylor Presentation July 2012

NRC Fukushima Tier 3 Report July 2012

NRC SOARCO Report NUREG-1935 January 2012

NRC Prioritization of Recommended Actions to be Taken in Response to Fukushima Lessons Learned SECY-11-0137 October 3, 2011 Sandia National Laboratories MELCOR Simulations of the Severe Accident at the Fukushima 1F1 Reactor 2012

Oak Ridge National Laboratory Enhanced Ex-Vessel Analysis for Fukushima Daiichi Unit 1: Melt Spreading and Core-Concrete Interaction Analyses with MELTSPREAD and CORQUENCH (ORNL/TM - 2012/455) February 2013

University of Michigan Fukushima US Research Response August 2012

- Science Fukushima Nuclear Fuel in a Reactor Accident March 2012

U.S. Department of Energy (DOE): Response to the Fukushima Daiichi Reactor Accident: Answers and Data Products for Decision Makers (http://journals.lww.com/health-physics/Abstract/2012/05000/U_S_DOE_s_Response_to_the_Fukushima_Daiichi.12.aspx)

U.S. Environmental Protection Agency (EPA): Response to the Fukushima Daiichi Nuclear Power Plant accident. (<http://www.ncbi.nlm.nih.gov/pubmed/22469933>)

U.S. Centers for Disease Control and Prevention: The Fukushima radiological emergency and challenges identified for future public health responses. (<http://www.ncbi.nlm.nih.gov/pubmed/22469934>)

Harvard University Preventing the Next Fukushima (<http://www.sciencemag.org/content/333/6049/1580.summary>)

Appendix D

Research Interest Subject Correspondence to CNSC Research Disciplines

*as per Appendix A

ORG.	RESEARCH INTERESTS	CNSC RESEARCH DISCIPLINES*									
		1	2	3	4	5	6	7	8	9	10
EPRI ¹	Hydrogen generation			X							
	Loss of off-site power			X							
	Reactor core performance following a loss of coolant			X							
	Iodine removal emergency response planning						X			X	
	Emergency diesel generator performance			X							
	Containment structural performance following an accident			X							
NRC ²	Tier 1.										
	Seismic and flood hazard re-evaluations		X								
	Seismic and flood walk downs		X								
	Station blackout (SBO) regulatory actions			X							
	Reliable hardened vents for Mark I and Mark II containments			X							
	SFP instrumentation			X							
	Strengthening and integration of emergency operating procedures, severe accident management guidelines (SAMGs), and extensive damage mitigation guidelines									X	

¹ Summary of EPRI Research Applicable to Nuclear Accident Scenarios, 1023403 Technical Update, June 2011

² Prioritization of Recommended Actions to be Taken in Response to Fukushima Lessons Learned, SECY-11-0137, October 3, 2011

ORG.	RESEARCH INTERESTS	CNSC RESEARCH DISCIPLINES*										
		1	2	3	4	5	6	7	8	9	10	
	Emergency preparedness regulatory actions (staffing and communications)										X	
	Tier 2.											
	SFP makeup capability			X								
	Emergency preparedness regulatory actions (the remaining portions not included in Tier 1)										X	
NRC (cont'd)	Tier 3.											
	Ten-year confirmation of seismic and flooding hazards		X									
	Potential enhancements to the capability to prevent or mitigate seismically induced fires and floods			X								
	Reliable hardened vents for other containment designs			X								
	Hydrogen control and mitigation inside containment or in other buildings			X								
	Emergency preparedness enhancements for prolonged SBO and multiunit events										X	
	Emergency Response Data System capability										X	
	Additional EP topics for prolonged SBO and multiunit events										X	
	EP topics for decision-making, radiation monitoring, and public education										X	
	Reactor Oversight Process modifications to reflect the recommended defense-in-depth framework		X							X		
	Staff training on severe accidents and resident inspector training on SAMGs		X								X	
	Additional Issues											
	Filtration of containment vents			X								
	Instrumentation for seismic monitoring			X								
Basis of emergency planning zone size										X		

ORG.	RESEARCH INTERESTS	CNSC RESEARCH DISCIPLINES*									
		1	2	3	4	5	6	7	8	9	10
	Pre-staging of potassium iodide beyond 10 miles					X					
	Transfer of spent fuel to dry cask storage			X							
	Loss of ultimate heat sink			X							
NRA ³	Development of safety evaluation methods for safety reviews		X								
	Technical Supports for strengthening of design basis			X							
	Safety management for the Specified Nuclear Power Facilities (SPFs)		X								
NRA (cont'd)	SA (Severe Accidents) measures at reactors and SPFs		X								
	Development of safety evaluation methods of safety culture							X			
JNES ⁴	Urgent Seven Projects										
	Study, Analysis and Evaluation on the Accident of Fukushima Daiichi Nuclear Power Plant		X	X		X	X	X		X	X
	Investigation and Evaluation for Environmental Impact at Fukushima Daiichi NPP Accident					X					
	Evaluation of Seismic Source, Ground Motion, Tsunami Based on the Tohoku Earthquake		X								
	Research Regarding Evaluation of Earthquake and Tsunami that Preceded it in Nuclear Reactors		X	X							
	Evaluation of Durability of SSCs Injected with Seawater		X	X							
	Study on Disaster Waste around Fukushima Dai-ichi NPP		X	X		X					
	Enhancement of Safety for Reprocessing Facilities		X	X							
	Examination for New Safety Regulation										
	Study on the Philosophy of Containment Basic Design Cooling Methods of Station Blackout Scenario for LWR Plants		X	X							
	Development of Tsunami Hazard Analysis – Study of size and frequency		X			X					

³ Nuclear Regulation Authority of Japan, written response to interview questions by Tadashi Yamada, March 29, 2013

⁴ JNES Annual Report April 2011 - March 2012

ORG.	RESEARCH INTERESTS	CNSC RESEARCH DISCIPLINES*										
		1	2	3	4	5	6	7	8	9	10	
	of giant tsunamis in the Pacific Ocean											
	Investigation of the Management of the Waste from Plant Accident					X						
	Proposal for a New Framework in Nuclear Emergency Response Based on Problem in East Japan Great Earthquake										X	
	Investigation into Criteria for the Termination of Nuclear Emergency and Countermeasures of the Radiation Exposure after Nuclear Emergency and Re-Entry										X	
	Development of Procedure for Emergency Response in the Case of Combined Disaster										X	
JNES (cont'd)	Developing Newly Necessary Evaluation Methods											
	Investigation of Evaluation Method for Marine Radiological Impact during an Accident					X						
	Seismic Assessment of Newly Installed Equipment for Emergency Electric Power Supply (Air-Cooled Type Equipment)		X	X								
	Evaluation of the Validity for the Work for Convergence at Fukushima Dai-ichi NPP Accident											
	Initial Event Analysis of the Fukushima Dai-ichi Accident		X	X								
	Long Term Cooling Analysis after Fukushima Dai-ichi Accident		X	X								
	Evaluation of Potential for Re-Criticality Fukushima Dai-ichi Reactors following Core Damage Accidents		X									
	Horizontal Development to Other Nuclear Power Plants											
	Study of Hydrogen Explosion Risk at Reactor Building during a Severe Accident		X	X								
	Test of Pressure Drop Related Characteristic during Cooling by Natural Convection of the Fast Breeder Reactor Plants			X								
Investigation of Safety Measures to Severe Accident in Fast Breeder Reactor		X	X									

ORG.	RESEARCH INTERESTS	CNSC RESEARCH DISCIPLINES*									
		1	2	3	4	5	6	7	8	9	10
JNES ⁵	Declining technical infrastructure - human resources development to maintain technical expertise/competence.							X			
OECD/ NEA ⁶	External and Internal Hazards Assessments		X								
	Plant Robustness and Defence-in-Depth Evaluations		X	X							
	Review of Safety Management Approaches		X								
	Assessment of Emergency Preparedness Methods and Approaches for Defining and Assessing Initiating External/Internal Events									X	
	Research Needed to Close Technical Knowledge Gaps (e.g., severe accident progression phenomenon, modelling of human behaviour under SA conditions, etc.)		X					X			
OECD/ NEA (cont'd)	Accident management and progression		X	X							
	Crisis Communications							X			
	Reassessment of Operating Experience		X	X							
	Balancing Deterministic and Probabilistic Approaches		X								
	Regulatory Infrastructure							X			
	Radiological Protection (RP) and Emergency Response							X		X	
	RP Aspects of Decontamination and Recovery					X	X				
IRSN ⁷	Better Understand Relevant Dangerous Phenomena and Associated Uncertainties and Cliff Edge Effects										
	Seismic hazards, and ground movement/plant response		X	X							
	Fuel behaviour in core: LOCA conditions, including water flow blockage, fuel relocation, fuel ejection(future CABRI international programme) or in spent fuel pools (cladding embrittlement under mixed steam/air conditions); criticality			X							

⁵ JNES - Regulatory Information Conferences (RIC) 2012 and 2013

⁶ OECD/NEA - Regulatory Information Conferences (RIC) 2012 and 2013

⁷ Institute de radioprotection et sureté nucleaire - Regulatory Information Conferences (RIC) 2012

ORG.	RESEARCH INTERESTS	CNSC RESEARCH DISCIPLINES*										
		1	2	3	4	5	6	7	8	9	10	
	Hydrogen generation (including during reflooding sequence) and accumulation			X								
	Efficiency of severe accident mitigation resources: in vessel core cooling capability, fuel/corium reflooding approach, containment venting filtering devices, corium/concrete interaction and cooling capability		X	X								
	Improve Severe Accident Modelling Capabilities											
	International benchmarking of Fukushima accidental sequences representation		X									
	Further development of the ASTEC Code (including for BWR and spent fuel pool accident consequences, and improvement of iodine chemistry modelling in the atmosphere following a release)		X			X						
	Better Understand Success or Failure Elements in HOF During Normal or Emergency Operations											
	Subcontracting practice										X	
	Emergency preparedness, including operator/public authorities/local stakeholders interaction										X	
IRSN (cont'd)	Improve and Disseminate With Decision Makers											
	Knowledge on severe accident economic and societal costs, in order to better appreciate cost/benefit factors in prevention measures											
KAERI ⁸	Design Basis External Events		X	X								
	Prolonged Station Blackout and Emergency Power			X								
	Reactor Parameter Monitoring During Accidents		X									
	Availability of Ultimate Heat Sinks			X								
	Passive Safety Systems in Emergency Cooling			X								
	Accident Management		X	X								

⁸ Korea Atomic Energy Research Institute - Regulatory Information Conferences (RIC) 2013

ORG.	RESEARCH INTERESTS	CNSC RESEARCH DISCIPLINES*									
		1	2	3	4	5	6	7	8	9	10
	Hydrogen Control			X							
	Safety of Spent Fuel Storage		X	X							
	Probabilistic Safety Assessment		X								
	Plant Siting and Site Layout		X	X							
COUNT TOTALS - CNSC RESEARCH DISCIPLINES			39	44		9	4	6		18	1

Appendix E

Research Project (Planned or Underway) Subject Correspondence to CNSC Research Disciplines

ORG.	RESEARCH PROJECTS – PLANNED OR UNDERWAY	CNSC RESEARCH DISCIPLINES									
		1	2	3	4	5	6	7	8	9	10
EPRI ^{9,10}	Seismic Research - guidance document for conducting plant-specific seismic walk downs		X								
	Seismic Research - re-evaluating the seismic hazards against the current NRC requirements and guidance and updating, as appropriate, the current ground motion attenuation model used in seismic hazard calculations		X								
	Severe Accident Management Guidelines - update to the technical basis		X							X	
	External Flooding - investigating risk-informed approaches for use in characterizing the safety significance of potential nuclear power plant flooding caused by natural events such as storm surges, river flooding, and local intense rainfall		X								
	Technical Evaluation of Fukushima Event - in-depth technical analysis focused on the accident progression and radiological contamination		X								
	Radiological Release Mitigation - assessing a number of strategies for mitigating radioactive releases from containment following a severe accident for boiling water reactor designs					X					
	Spent Fuel Pools (SPF) - research related to the safe operation, monitoring and analysis of spent fuel pool behavior			X							
	Post -Accident Monitoring - investigating several advanced instrumentation technologies in use in other industries that would be able to function for extended periods of time with limited to no external power supply			X							
	Battery Capability Testing - research to more accurately characterize battery response and performance capability over long periods of time during station blackout conditions			X							

⁹ Fukushima-Related Research Activities, An EPRI Progress Report, 102582, August 2012

¹⁰ EPRI considers that no major changes were required to its fundamental research activities as a result of Fukushima. However, many accelerations and priority changes were undertaken. A few new areas of research include Radiological Releases in Severe Accidents and Accident Tolerant Fuels (interview with Ken Canavan, Director of Plant Technology EPRI, February 25, 2013).

ORG.	RESEARCH PROJECTS – PLANNED OR UNDERWAY	CNSC RESEARCH DISCIPLINES									
		1	2	3	4	5	6	7	8	9	10
	Accident Tolerant Fuels – research fuel that has a higher melting temperature and longer melting time (not included in the August 2012 Newsletter)			X							
NRC ¹¹	Filtered Containment Venting System			X							
	Hydrogen Control and Mitigation Inside Containment or in Other Buildings			X							
	Station Blackout Mitigation Strategies			X							
	Extended Battery Operation Study			X							
NRC (cont'd)	Research on Aqueous Pathways Resulting from Severe Accidents			X							
	Spent Fuel Pool Scoping Study (SFPSS)			X							
	Site Level 3 Probabilistic Risk Assessment (PRA)		X								
NRC/ ONR ¹²	Periodic Confirmation of Seismic and Flooding Hazards		X								
	Potential Enhancements to the Capability To Prevent or Mitigate Seismically Induced Fires and Floods			X							
	Reliable Hardened Vents for Other Containment Designs			X							
	Hydrogen Control and Mitigation Inside Containment or in Other Buildings			X							
	Emergency Preparedness (EP) Enhancements for Prolonged SBO and Multiunit Events, Emergency Response Data System Capability									X	
	Additional EP Topics for Prolonged SBO and Multiunit Events, EP Topics for Decision making, Radiation Monitoring, and Public Education									X	
	Reactor Oversight Process Modifications To Reflect the Recommended Defense-in-Depth Framework		X								
	Staff Training on Severe Accidents and Resident Inspector		X					X		X	
	Training on Severe Accident Mitigation Guidelines Program Plan for Basis of Emergency Planning Zone Size		X					X		X	
	Pre-staging of Potassium Iodide Beyond 10 Miles					X					
	Transfer of Spent Fuel to Dry Cask Storage			X							
	Enhanced Reactor and Containment Instrumentation Withstanding Beyond-Design-Basis			X							

¹¹ NRC Regulatory Information Conferences (RIC) 2012 and 2013

¹² NRC/ONR - Program Plans for Tier 3 Recommendations, Enclosure 3, SECY-12-0095

ORG.	RESEARCH PROJECTS – PLANNED OR UNDERWAY	CNSC RESEARCH DISCIPLINES											
		1	2	3	4	5	6	7	8	9	10		
	Conditions												
JNES ¹³	Seismic and Tsunami Hazard Evaluation		X										
	Upgrading of Accident Management Measures - Thermal-Hydraulic Safety Research & Fuel Safety Research		X										
	Hydrogen Mixing and Detonation Behavior			X									
	Environmental Consequence Analysis (Level 3 PSA)					X							
	Experimental Study on Scrubbing under CV Wet Venting			X									
JNES (cont'd)	Research on Effective Cooling of Containment Vessel			X									
	Experimental Study on Seawater and Boric Acid Injection			X									
	Thermal-Hydraulic Tests on LOCA at Spent Fuel Pool involving fuel cooling procedures using spray cooling system and others available means			X									
	Fostering internal safety culture and developing safety culture evaluation methods for both licensees and regulatory body								X				
	Off-site Radiological Effect on Residents and Workers					X							
OECD/ NEA ¹⁴	Gap analysis based on research issues from Fukushima - possible expansion of existing projects and/or new R&D project proposals		X	X		X	X	X		X	X		
	Committee on the Safety of Nuclear Installations (CSNI) review of research direction		X	X		X	X	X		X	X		
	Human Performance and Intervention under Extreme Conditions							X					
	Electrical System Robustness in Light of Fukushima			X									
	Position Paper on Filtered Containment Venting			X									
	International Benchmarking on Fast-Running Software Tools Used to Model Fission		X	X									
	Product Releases During Accidents					X							
	Position Paper on Hydrogen Generation and Mitigation		X	X									
Metallic Component Margins under High Seismic Loads		X	X										

¹³ JNES - Regulatory Information Conferences (RIC) 2012 and 2013

¹⁴ OECD/NEA - Regulatory Information Conferences (RIC) 2012 and 2013

ORG.	RESEARCH PROJECTS – PLANNED OR UNDERWAY	CNSC RESEARCH DISCIPLINES									
		1	2	3	4	5	6	7	8	9	10
	Workshop on PSA of Natural External Events Including Earthquakes		X								
	Benchmark Study on the Accident of Fukushima - analyze accident progression and current status inside RPVs and PCVs; improve methods and models of codes and reduce uncertainties in SA analysis		X								
GRS ¹⁵	In-Depth Investigation of Accident and Phenomena										
	Collection of information on plant design, design base loads, natural impact and course of the accident (collaboration with JNES)		X	X							
	Detailed data analysis: “reconstruct” the accident sequence; identification of key events and major phenomena occurred		X	X							
	Thermal-Hydraulic Analyses (ATHLET-CD/COCOSYS)										
	“Fukushima-like” model based on BWR 69 with boundary conditions from accident analysis		X	X							
GRS (cont’d)	Analysis of different accident phases with regard to H2 generation and to radioactive source term		X	X							
	Assessment of relevance for German NPPs by calculating the behaviour of a German PWR exposed to a similar hazard		X	X							
	Response to Natural External Hazards										
	Study transferability of earthquake and flooding impacts (combination + fire) to German NPPs: general specification of beyond design natural hazards		X	X							
	Analysis of the protection of German NPPs against beyond design impacts		X	X							
	Recommendations to improve protection in case of weaknesses identified			X							
	Vulnerability of Electrical Power Supply										
	Analysis of layout of Japanese electrical grid		X	X							
	Analysis of consequences of earthquake, tsunami to the power and emergency power supply		X								
	Assessment of the behaviour of power supply in German NPPs under analogue conditions		X	X							
	Recommendations for German grid and emergency power supply if necessary			X							
	Analysis Of Accident Management Measures										
	Assessment of feasibility and effectiveness of AM measures in German NPPs under		X								

¹⁵ GRS - Regulatory Information Conferences (RIC) 2012 and 2013

ORG.	RESEARCH PROJECTS – PLANNED OR UNDERWAY	CNSC RESEARCH DISCIPLINES									
		1	2	3	4	5	6	7	8	9	10
	Fukushima-like conditions (long lasting SBO and loss of UHS, damaged infrastructures)										
	Identification of weak points and suggestion of possible improvements and extensions			X							
	Investigation Of Cliff-Edge Effects in AM										
	Dynamic PSA analyses in combination with MELCOR calculations plus uncertainty analysis for a specific scenario at a German PWR		X								
	Identification of grace periods for AM actions (bleeding, feeding, venting) to avoid core damage		X	X							
	In-Depth Investigation of Accident and Phenomena										
	Collection of information on plant design, design base loads, natural impact and course of the accident (collaboration with JNES)		X	X							
	Detailed data analysis: “reconstruct” the accident sequence; identification of key events and major phenomena occurred		X	X							
	Development of Methods for Assessment of Decision Making Processes										
	Investigation of the effect of factors of influence (e.g. time pressure, information overflow) on communication, collaboration and shared decision making in emergency								X		
GRS (cont’d)	Development of an approach (on the basis of the factors of influence) to assess the adequacy of decisions by the emergency response team								X		
	Adaptation of FMEA for Cable Fire to Flooding Events										
	Adaptation of Failure Mode and Effect Analysis methodology (available for fire) to flooding events by analysing damage states of cable and electrical systems in humid or wet environments		X	X							
	Prerequisite to the prediction of safety relevant consequences of postulated water levels due to internal or external flooding in specific building areas of German PWRs		X	X							
	Critical Review of The Modelling of Specific Phenomena in German SA Codes										
	Test of coupled simulation tools ATHLET-CD/COCOSYS with respect to selected SA phenomena (model based on BWR 69) - cooling of partly molten core and fission product release from core; fission product retention inside the wetwell of BWR plants; pool scrubbing specifically for saturated water conditions; and fission product retention in filtered venting; hydrogen distribution in the reactor building		X	X							
	Structural mechanics analysis of dynamic containment behaviour - latest PWR type (KONVOI) under beyond design earthquake loads (primary earthquake and aftershock loads); determination of floor response spectra and loads to components and piping structures		X	X							

ORG.	RESEARCH PROJECTS – PLANNED OR UNDERWAY	CNSC RESEARCH DISCIPLINES									
		1	2	3	4	5	6	7	8	9	10
	Spent fuel pool behaviour during severe accident sequences , application of analytical tools ASTEC and MELCOR - PWRs and BWRs under Station Black-out conditions; Two operational cases (starting from normal power operation & core fully unloaded to SFP); Phenomena: cooling of partially uncovered FAs , combined cladding oxidation by steam and air, zircon fire, relocation of molten material, fission product release		X	X							
STUK ¹⁶	Man, Organization and Society										
	Review of lessons learned from reported events (e.g. Fukushima) which have design as a contributing factor		X	X							
	Fuel Research and Reactor Analysis										
	Development of tools and methods to enable an informed assessment of the distribution of radionuclides in various fuel microstructures		X	X							
	Thermal Hydraulics										
	OECD/PKL3 project: "Fukushima" test scenario		X	X							
	Severe Accidents										
Estimation of the radiation doses caused by the Fukushima accident in the environment of the Fukushima Dai-ichi power plant					X						
STUK (cont'd)	Investigation of liquid metal, liquid oxide slag and salt liquid/solid phases interactions			X		X					
	Development of MELCOR models of the Fukushima accident		X								
	Development of an analysis tool for studies of loss of coolant accidents in spent fuel pools in the reactor building		X	X							
	Probabilistic Risk Assessment										
	More detailed studies of the occurrence of natural hazards: very rapid changes of Baltic Sea level, ice storms, excess snowfall cases and hurricane scale wind speeds, seismic hazard		X								
IAEA ¹⁷	Seismic Hazards - methodology for including diffuse seismicity in hazard assessment; fault displacement computational methodology; and methodology for utilization of paleo-seismicity		X								
	Seismic Design - state of the art on the practice of base isolation in nuclear installations		X	X							
	Seismic Experience – development of seismic experience database		X								

¹⁶ Radiation And Nuclear Safety Authority, Finland - Regulatory Information Conferences (RIC) 2013

¹⁷ IAEA - Regulatory Information Conferences (RIC) 2013

ORG.	RESEARCH PROJECTS – PLANNED OR UNDERWAY	CNSC RESEARCH DISCIPLINES										
		1	2	3	4	5	6	7	8	9	10	
	External Events Preparedness & Response - state of the art practices in the use of damage indicating parameters in pre- and post-earthquake preparedness and response		X								X	
	Tsunami Hazards - design of tsunami protection measures			X								
	External Events Safety Assessment of Multi-Unit Sites - safety assessment of multi-unit sites against multiple hazards		X									
	Collaboration (USGS,NOAA, JNES & USNRC) - External Event Notification System		X									
KAERI ¹⁸	Thermal-Hydraulic Safety											
	Securing Ultimate Heat Sinks for Severe Accident Prevention - integral simulation of extreme situations (e.g., Prolonged SBO) using the ATLAS facility; development/verification/assessment of passive safety features for advanced reactor systems; and coolability of deformed fuels: tests & analyses		X	X								
	Advanced Simulation of T/H Behaviors - development & application of component T/H analysis code, CUPID; coupled analysis of neutronics, component T/H, and system T/H; advanced physical models based on high-precision experiments		X	X								
	Develop Effective Mitigation Measures for Severe Accidents											
	Develop Analysis Code and Methodology: COMPASS+SPACE;TROI (OECD /SERENA); Steam Explosion; VESTA: Corium-Structure Interaction; Integrity of Containment: Hydrogen, Filtered Venting, Fission Product		X	X								
KAERI (cont'd)	Risk Assessment & Management											
	Full-Scope Risk Assessment Framework - internal (including fire/flooding); external events (seismic, tsunami, airplane crash, and other external events such as the super typhoon, etc.);full-power/low-power/shutdown mode PSA; assessment of SFP risks & multi-unit risk; new system characteristics: passive systems, digital I&C, etc.; improvement of the PSA engine, FTREX		X	X								
	Site Risk Profiles for Korean NPPs		X									
	The technical basis for the integrated EOP/SAMG/EDMG and risk-informed Emergency Preparedness		X								X	
	COUNT TOTALS - CNSC RESEARCH DISCIPLINES		56	58		9	2	8		9	2	

¹⁸ Korea Atomic Energy Research Institute - Regulatory Information Conferences (RIC) 2013

Appendix F

Research Project (Completed) Subject Correspondence to CNSC Research Disciplines

ORG.	RESEARCH PROJECTS – COMPLETED	CNSC RESEARCH DISCIPLINES									
		1	2	3	4	5	6	7	8	9	10
EPRI ¹⁹	Station Blackout Reports		X								
	Hydrogen Generation-Related Reports			X							
	Advanced Containment Experiments (ACE) Phase B – Containment Iodine Behavior Reports			X							
	Advanced Containment Experiments (ACE) Phase C – Molten Corium Concrete Interaction (MCCI) Reports			X							
	Other reports on MCCI			X							
	Containment Response to Missiles and Earthquakes		X								
	Emergency Planning									X	
	Iodine Removal					X					
EPRI ²⁰	Investigation of Strategies for Mitigating Radiological Releases in Severe Accidents BWR Mark I and Mark II Studies			X		X	X				
NRC ²¹	State-of-the-Art Reactor Consequence Analysis (SOARCA)		X								
	Fukushima Accident Analysis using Computer codes such as		X								

¹⁹ Summary of EPRI Research Applicable to Nuclear Accident Scenarios, 1023403 Technical Update, June 2011 - listing of past research relevant to research issue areas identified

²⁰ EPRI, 2012 Technical Report

²¹ US NRC Regulatory Information Conferences (RIC) 2012 and 2013

ORG.	RESEARCH PROJECTS – COMPLETED	CNSC RESEARCH DISCIPLINES									
		1	2	3	4	5	6	7	8	9	10
	MELCOR										
JNES ²²	Upgrading of SA Progression and Source Term Analysis - Fukushima accident analysis with MELCOR & TEPCO's analysis with MAAP		X								
	Environmental Consequence Analysis - using the source terms with MELCOR & OSCAAR		X			X					
OECD/NEA ²³	Comprehensive review of past safety research		X	X		X	X	X		X	X
Sandia National Laboratories ²⁴	MELCOR Simulations of the Severe Accident at the Fukushima 1F1 Reactor		X								
WHO ²⁵	Health risk assessment from the nuclear accident after the 2011 Great East Japan Earthquake and Tsunami						X				
TEPCO ²⁶	Estimation of Radioactive Material Released to the Atmosphere during the Fukushima Daiichi NPS Accident					X					
Oak Ridge National Laboratory ²⁷	Enhanced Ex-Vessel Analysis for Fukushima Daiichi Unit 1:Melt Spreading and Core-Concrete Interaction Analyses with MELTSPREAD and CORQUENCH		X	X							
European Commission ²⁸	Fukushima's effects on nuclear policy in Germany and the UK										X

²² JNES - Regulatory Information Conferences (RIC) 2012 and 2013

²³ OECD/NEA - Regulatory Information Conferences (RIC) 2012 and 2013

²⁴ Sandia National Laboratories, 2012

²⁵ World Health Organization, 2013

²⁶ Tokyo Electric Power Company, May 2012

²⁷ Oak Ridge National Laboratory, (ORNL/TM - 2012/455), February 2013

²⁸ Environmental Science & Policy 15:1-3, 2012

ORG.	RESEARCH PROJECTS – COMPLETED	CNSC RESEARCH DISCIPLINES									
		1	2	3	4	5	6	7	8	9	10
	radioisotope contamination.										
Harvard University ³⁷	Preventing the Next Fukushima		X	X		X	X	X		X	X
Seinan Gakuin University ³⁸	Experience of technological and natural disasters and their impact on the perceived risk of nuclear accidents after the Fukushima nuclear disaster in Japan 2011: A cross-country analysis										X
University of Singapore ³⁹	Fukushima and thereafter: Reassessment of risks of nuclear power		X	X		X	X	X		X	X
COUNT TOTALS - CNSC RESEARCH DISCIPLINES			11	10		11	9	3		8	8

³⁷ Belfer Center for Science and International Affairs, Harvard University, Science 16 September 2011: Vol. 333 no. 6049 pp. 1580-1581

³⁸ Seinan Gakuin University, Japan, The Journal of Socio-Economics, 2012, vol. 41, issue 4, pages 360-363

³⁹ National University of Singapore, Energy Policy, Volume 52, January 2013, Pages 726–736

Appendix G

Completed Research Projects – Analysis of Where Research Was Done

1 – Non-Profit 2 – Government Agencies 3 - Private Sector 4 – Universities 5 – International Agencies

ORG.	RESEARCH PROJECTS – COMPLETED	RESEARCH PERFORMERS				
		1	2	3	4	5
EPRI ⁴⁰	Station Blackout Reports	x				
	Hydrogen Generation-Related Reports	x				
	Advanced Containment Experiments (ACE) Phase B – Containment Iodine Behavior Reports	x				
	Advanced Containment Experiments (ACE) Phase C – Molten Corium Concrete Interaction (MCCI) Reports	x				
	Other reports on MCCI	x				
	Containment Response to Missiles and Earthquakes	x				
	Emergency Planning	x				
	Iodine Removal	x				
EPRI ⁴¹	Investigation of Strategies for Mitigating Radiological Releases in Severe Accidents BWR Mark I and Mark II Studies	x				
NRC ⁴²	State-of-the-Art Reactor Consequence Analysis (SOARCA)	x				

⁴⁰ Summary of EPRI Research Applicable to Nuclear Accident Scenarios, 1023403 Technical Update, June 2011 - listing of past research relevant to research issue areas identified

⁴¹ EPRI, 2012 Technical Report

⁴² US NRC Regulatory Information Conferences (RIC) 2012 and 2013

ORG.	RESEARCH PROJECTS – COMPLETED	RESEARCH PERFORMERS				
		1	2	3	4	5
	Fukushima Accident Analysis using Computer codes such as MELCOR	x				
JNES ⁴³	Upgrading of SA Progression and Source Term Analysis - Fukushima accident analysis with MELCOR & TEPCO's analysis with MAAP		x			
	Environmental Consequence Analysis - using the source terms with MELCOR & OSCAAR		x			
OECD/NEA ⁴⁴	Comprehensive review of past safety research					x
Sandia National Laboratories ⁴⁵	MELCOR Simulations of the Severe Accident at the Fukushima 1F1 Reactor			x		
WHO ⁴⁶	Health risk assessment from the nuclear accident after the 2011 Great East Japan Earthquake and Tsunami					x
TEPCO ⁴⁷	Estimation of Radioactive Material Released to the Atmosphere during the Fukushima Daiichi NPS Accident			x		
Oak Ridge National Laboratory ⁴⁸	Enhanced Ex-Vessel Analysis for Fukushima Daiichi Unit 1:Melt Spreading and Core-Concrete Interaction Analyses with MELTSPREAD and CORQUENCH			x		
European Commission ⁴⁹	Fukushima's effects on nuclear policy in Germany and the UK					x
Dalhousie	The policy responses to the Fukushima nuclear accident and their effect on Japanese energy security				x	

⁴³ JNES - Regulatory Information Conferences (RIC) 2012 and 2013

⁴⁴ OECD/NEA - Regulatory Information Conferences (RIC) 2012 and 2013

⁴⁵ Sandia National Laboratories, 2012

⁴⁶ World Health Organization, 2013

⁴⁷ Tokyo Electric Power Company, May 2012

⁴⁸ Oak Ridge National Laboratory, (ORNL/TM - 2012/455), February 2013

⁴⁹ Environmental Science & Policy. 15:1-3, 2012

ORG.	RESEARCH PROJECTS – COMPLETED	RESEARCH PERFORMERS				
		1	2	3	4	5
University ⁵⁰						
World Energy Council ⁵¹	World Energy Perspective: Nuclear Energy One Year After Fukushima					x
CFPR ⁵²	The Fukushima Nuclear Accident – Shift in Canada’s Nuclear Energy Policy?	x				
JAEA ⁵³	Emergency response by robots to Fukushima-Daiichi accident: summary and lessons learned		x			
U.S. DOE ⁵⁴	U.S. DOE’s Response to the Fukushima Daiichi Reactor Accident: Answers and Data Products for Decision Makers		x			
U.S. EPA ⁵⁵	U.S. EPA response to the Fukushima Daiichi Nuclear Power Plant accident.		x			
U.S. CDPC ⁵⁶	The Fukushima radiological emergency and challenges identified for future public health responses.		x			
Nara Medical University ⁵⁷	The disaster at Japan's Fukushima-Daiichi nuclear power plant after the March 11, 2011 earthquake and tsunami, and the resulting spread of radioisotope contamination.				x	
Harvard University ⁵⁸	Preventing the Next Fukushima				x	

⁵⁰ Energy Research Group, Dalhousie University, September 2012

⁵¹ World Energy Council, UK, 2011

⁵² Canadian Forum for Policy Research, 2012

⁵³ Japan Atomic Energy Agency, Industrial Robot: An International Journal, Vol. 39 Iss: 5, pp.428 – 435, 2012

⁵⁴ US Department of Energy, Health Physics: May 2012 - Volume 102 - Issue 5 - p 557–562

⁵⁵ United States Environmental Protection Agency, Health Phys. 2012 May;102(5):563-9.

⁵⁶ Centers for Disease Control and Prevention, Health Phys. 2012 May;102(5):584-8.

⁵⁷ Nara Medical University, Japan, Radiat Res. 2012 Jan;177(1):1-14. Epub 2011 Nov 7

ORG.	RESEARCH PROJECTS – COMPLETED	RESEARCH PERFORMERS				
		1	2	3	4	5
Seinan Gakuin University ⁵⁹	Experience of technological and natural disasters and their impact on the perceived risk of nuclear accidents after the Fukushima nuclear disaster in Japan 2011: A cross-country analysis				x	
University of Singapore ⁶⁰	Fukushima and thereafter: Reassessment of risks of nuclear power				x	
COUNT TOTALS - RESEARCH PERFORMERS		13	6	3	5	4

⁵⁸ Belfer Center for Science and International Affairs, Harvard University, Science 16 September 2011: Vol. 333 no. 6049 pp. 1580-1581

⁵⁹ Seinan Gakuin University, Japan, The Journal of Socio-Economics, 2012, vol. 41, issue 4, pages 360-363

⁶⁰ National University of Singapore, Energy Policy, Volume 52, January 2013, Pages 726–736