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Summary Report of the International Workshop on Multi-Unit Probabilistic Safety Assessment

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We will never compromise safety.
Nous ne compromettrons jamais la sûreté.

Summary Report of the International Workshop on Multi-Unit Probabilistic Safety Assessment

This summary report was prepared by Karl Fleming with contributions from George Apostolakis, Eliseo Chan, Fred Dermarkar, Gabriel Georgescu, Raducu Gheorghe, Mohammad Modarres, Marina Röwekamp, Tsuyoshi Takada and Smain Yalaoui.

Forward

The Canadian Nuclear Safety Commission (CNSC) organized and hosted an International Workshop on Multi-Unit Probabilistic Safety Assessment (MUPSA) in Ottawa, Canada from November 17 – 20, 2014. This workshop was devoted to sharing information on PSAs for multi-unit sites, as well as the development of whole-site safety goals. This was just a beginning for regulators and the PSA community to explore this uncharted area, and we will continue to be engaged as we ask for ongoing cooperation and support from the international community.

The report of the MUPSA workshop is being published in order to further share the knowledge and practical experiences presented at the workshop, and to summarize the significant insights and observations identified by the workshop co-chairs and advisor.

We hope that the workshop and its information will serve those who are conducting or considering PSA for multi-unit sites. The workshop participants agreed that MUPSA is a new approach, and that cooperation and collaboration among the international community is especially important in order to leverage resources and to further serve the public interest. Safety is always a priority, and this workshop furthered enhanced safety.

Acknowledgements

The success of the International Workshop on MUPSA can be attributed to the efforts, expertise and professionalism of many. I would firstly like to thank Karl Fleming for his excellent work in consolidating the workshop summary. I would also like to thank George Apostolakis, the Workshop Technical Advisor for providing valuable advice and guidance, as well as the Co-chairs Eliseo Chan, Fred Dermarkar, Gabriel Georgescu, Raducu Gheorghe, Mohammad Modarres, Marina Röwekamp, Tsuyoshi Takada and Smain Yalaoui for their dedication and contributions. Additional appreciation goes to the planning and logistics team of Michael Xu, Usha Menon, and Christine Delaney. Last, but certainly not least, I would also like to extend my sincere gratitude to all of the workshop presenters and participants for their excellent presentations and also for imparting their valuable experiences and thoughts on MUPSA.

Yolande Akl
Director/Workshop Chairperson,
International Workshop on Multi-unit Probabilistic Safety Assessment
November 17-20, 2014, Ottawa, Canada

Executive Summary

The Canadian Nuclear Safety Commission (CNSC) hosted the International Workshop on Multi-Unit Probabilistic Safety Assessment (PSA) in Ottawa, on November 17–20, 2014. Invitees included eminent international experts (regulators, academics, consulting organizations and industry leaders) to share their experience on the topic of MUPSA and site-based safety goals.

Many prestigious PSA experts from around the world attended the workshop, including staff representing the Working Group on Risk Assessment (WGRisk), the International Atomic Energy Agency (IAEA) and the United States Nuclear Regulatory Commission (USNRC).

Overall, one hundred seventeen participants from fourteen countries and the IAEA attended the workshop. This workshop provided an excellent forum for sharing new ideas and experiences in order to develop the methodology for MUPSA and whole-site Safety Goals. There were a total of thirty-six presentations made during the four technical sessions, covering all of the thematic areas of the workshop. Each technical session was followed by a one-hour guided discussion.

Main topics covered during the workshop included:

- methodological challenges in performing MUPSAs;
- site-based risk metrics;
- challenges in establishing safety goals for whole sites; and
- risk aggregation across all units and all hazards.

After the workshop, the feedback received from participants was very positive and all agreed that this was a good learning experience as it provided the opportunity for international experts to evaluate the state-of-the-practice in assessing the risks from multi-unit stations.

The workshop report consists of a summary report of all the technical sessions, including summaries of the presentations and the guided discussions. The list of participants, workshop agenda and all presentations are included (presentations can be made available on request).

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1. Introduction

1.1 Background

The Fukushima Daiichi reactor accident in March 2011 clearly demonstrated the likelihood of an accident involving nearly concurrent core damage at multiple reactor units and spent fuel pools. The cause of this accident was the inundation of the site by a large tsunami triggered by the 2011 earthquake originating off the eastern coast of Japan. Emergency response teams and resources were overwhelmed, and tried to cope with the severe damage to all six reactor units and their spent fuel storage facilities. The accident progression involved core damage to three reactor units and was influenced by complex interactions involving operator actions to protect each facility, as well as interactions and dependencies among the facilities. Fortunately, the initial response of the plant safety systems and emergency measures were successful in delaying releases and allowed for evacuations and the prevention of significant radiological exposures.

Increasingly, there is recognition of the critical need for the evaluation of site risk in an integrated way, which includes consideration of the potential for accidents involving multiple installations concurrently, and in an appropriate way, to integrate the various risk contributions from different sources, hazard groups and plant operating states. The international nuclear community is making serious efforts in collecting best practices while developing and reaching consensus on how the MUPSA should be conducted and on how multi-unit and site-based safety goals should be defined and evaluated.

In Canada, the Fukushima Daiichi accident led to the amendment of the Canadian Nuclear Safety Commission (CNSC)'s regulatory standard S-294 *Probabilistic Safety Assessment (PSA) for Nuclear Power Plants*. Re-published in 2014, this regulatory standard now explicitly requires the consideration of other radioactive sources, their potential combinations of external events, and multi-unit impacts. Following a Nuclear Energy Agency (NEA) assessment of the Fukushima Daiichi incident, the Working Group on Risk Assessment (WGRISK), comprised of experts on PSA, considered developing a work stream in the area of MUPSA. Such a work stream would need a review of current knowledge and practices in this area.

In January 2014, Canadian utilities under the CANDU Owners Group (COG) held an "International Workshop on Whole-Site Characterization" in Toronto, Canada. Additionally, an international workshop on MUPSA was organized and hosted by the CNSC in November 2014 in Ottawa, Canada, and was a continuation of Canadian and international efforts in the field of safety assessment of multi-unit sites. It included a series of exploratory discussions that will become part of the solid underpinning for development of an NEA WGRISK Committee on Safety in Nuclear Institutions (CSNI) Activity Proposal Sheet (CAPS) on MUPSA.

The workshop provided an opportunity to present the safety reports being developed by the International Atomic Energy Agency (IAEA) in the area of MUPSA. It also provided a framework for performing future MUPSAs, sharing lessons learned and exchanging knowledge regarding the latest developments in MUPSA, as well as whole-site safety goals. The purpose of this report is to summarize the highlights of this workshop.

1.2 Objectives

The objectives of the workshop were to:

- Share the latest insights and findings regarding the development and application of MUPSA;
- identify possible risk metrics for multi-unit sites;
- discuss whole-site safety goals and the role of the safety goals in the licensing process;
- develop ongoing research programs on multi-unit NPP severe-accident progression and management, and
- investigate additional issues.

1.3 Report Guide

The major findings and outcomes of the workshop are provided in section 2 and are organized into the following topics: The current international status of MUPSA, technical issues and challenges faced in advancing the state-of-practice in MUPSA, selection of risk metrics and safety goals for use in risk-informed decision making in the MUPSA context, and future actions to address the challenges in moving forward with multi-unit and site-based risk assessments. A summary of the workshop sessions, subsequent discussions, and presentations are provided in section 3. The discussions include a number of recommendations where advancing MUPSA technology can be identified.

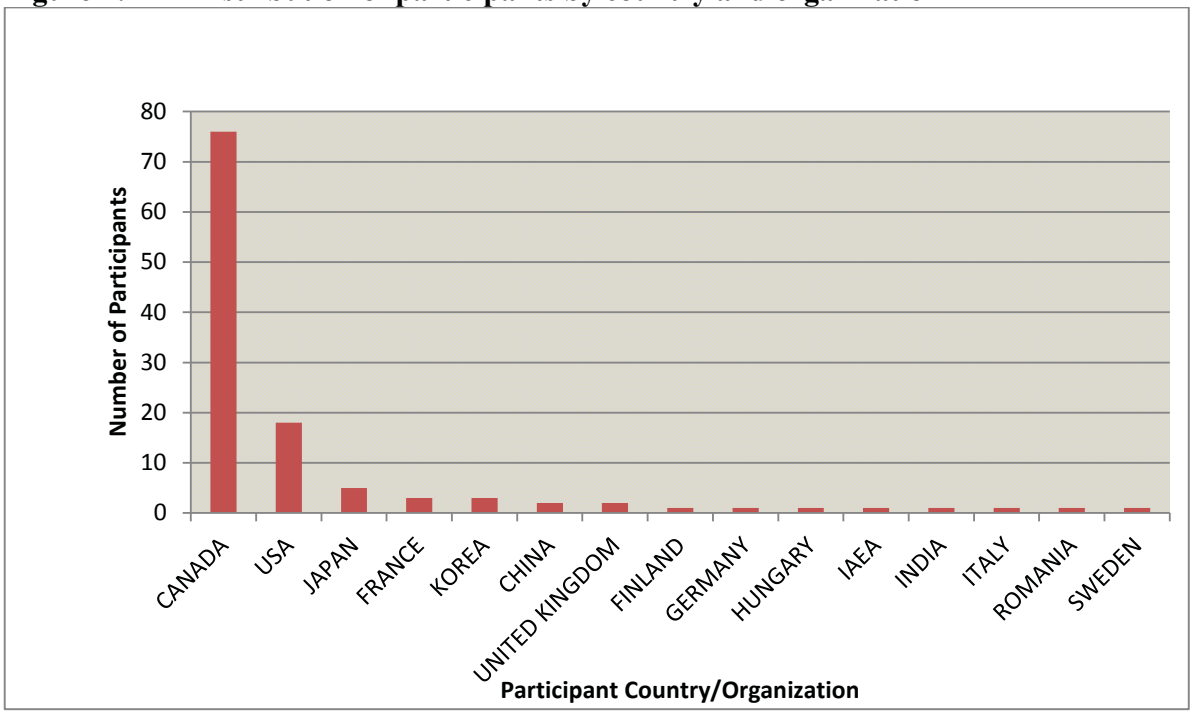
2. Findings

2.1 Overview

The workshop was conducted over a four days and was organized into an opening session, a series of six technical sessions and a closing plenary session. Each session included a set of topical presentations. Time was allotted for comments and discussions among the one hundred and seventeen workshop participants from fourteen countries and the IAEA (distribution shown in Figure 1). The technical sessions included the following topics (number in parentheses indicates the number of half-day sessions devoted to each topic):

- Selection of risk metrics for multi-unit sites (1)
- Role of site safety goals in the licensing process (1)
- Experience with MUPSA (3)
- Challenges in MUPSA (1)

Figure 1: Distribution of participants by country and organization



From the presentations and subsequent valuable discussions, a set of workshop findings were derived. These findings are expressed in the following statements:

- The workshop provided an opportunity to capture the current international status of development and practice in the areas of MUPSA and site safety goals.
- The main technical issues and challenges for MUPSA were identified; the extent to which the lack of progress in MUPSA reflected a limitation in the state-of-practice versus the state-of-technology was discussed and debated.
- Treatment of human actions and organizational dependencies in modelling multiple reactor accidents stands out as arguably the most important challenge in advancing MUPSA.
- Several technical approaches and tools for performing MUPSA and defining site-based risk metrics were presented, and the similarities in the approaches presented far outweighed the differences.
- The importance of utilizing operational experience for multi-unit risk insights was highlighted, especially in the discussions following the presentations.

- The important roles of Level 3 PSA and radiological consequence analyses to calibrate frequency-based risk metrics were highlighted in the presentations and discussions.
- The task of rethinking the hierarchy of qualitative safety goals and quantitative design objectives to incorporate site and multi-unit accident considerations is a work in progress.

These findings can be organized into three topical areas, including:

a) Characterization of the current international status of MU PSA;
b) Technical issues and challenges for MUPSA; and
c) Actions to move forward with meeting the technical challenges.

A summary of the workshop findings in each of these respective areas is provided in the following sections.

2.2 Current International Status of MUPSA

A summary of the status of MUPSA in each participating country and the IAEA, based on information from the workshop presentations and discussions is provided in Table 1. It should be emphasized that there may be additional MUPSA activities underway in other countries. However, the fact that there were one hundred and seventeen participants from fourteen different countries and international organizations provided the opportunity to capture a large fraction of world activity in this area.

From the information collected, it is apparent that Canada is leading the international community in MUPSAs. Current and previous PSAs have continued to work with single unit risk metrics such as Core Damage Frequency (CDF) and Large Release Frequency (LRF) that have been adapted to CANDU design features. However, multi-unit accidents have been included, specifically the contributions from adjacent accident units, as well as the common mode events affecting all units concurrently. Planning is underway for a more integrated site-based PSA of an existing multi-unit CANDU NPP to integrate the risk contributions from single and multi-unit accidents and aggregates risk contributions across the applicable hazards and operating states. Canadian regulators are actively developing site-based safety goals to support Risk Informed Decision Making (RIDM) and addressing risk communication to the public. In addition to the current workshop, COG also organized an international workshop on MUPSA in January 2014, and many presentations by the CNSC, COG and other participating organizations indicated efforts in seeking a path forward for both MUPSA and implementation of site safety goals.

In response to requests from member states following the 2007 earthquake at Kashiwazaki-Kariwa, Japan, and amplified by concerns following the 2011 Fukushima Daiichi accident, the

International Seismic Safety Centre (ISSC) Working Area 8 (WA8) was formed within the IAEA to develop guidance needed to support MUPSAs. One of the topics discussed at length during the workshop was a safety report being developed by WA8 that provides technical guidance for performance of an integrated multi-unit site PSA. This report will be published in 2015. Additionally, IAEA reports and safety guides are being developed, and some previous reports on PSA are currently being revised to address MUPSA issues.

MUPSAs have been previously developed in the United States, and the USNRC is currently performing a Level 3 PSA research project in which releases from multiple reactor units and spent fuel storage facilities at an existing two-unit site are to be analyzed. Other countries, such as India, France and Japan, are at various stages of considering MUPSAs. It is reasonable to expect that in several years there will be a significant increase in the body of completed technical work to mark the advancement in the state-of-practice in MUPSAs worldwide.

2.3 Technical Issues and Challenges in Performing MUPSAs

Given the excellent participation at the workshop by those who have performed, or are in the process of performing MUPSA, the workshop provided a great opportunity to identify the technical issues and challenges in performing such a PSA. A summary of those issues and challenges which were discussed and presented during the workshop are included in Table 2. The state-of-practice in PSA was primarily confined to the consideration of single reactor accidents, and in nearly all cases, excludes the consideration of accidents involving other radionuclide sources outside the reactor coolant system, such as the spent fuel storage systems. The scope of single reactor PSAs has been extended to account for all internal and external hazards and accidents that could initiate during full power, low power and shutdown plant operating states. In the early development of PSA, the scope was often extended to Level 3, in which the risks of off-site population radiation exposures, health effects and land contamination were addressed. Later, it has been more common to limit the scenario development to the extent that allows the estimation of frequency-based surrogate risk metrics such as CDF and Large (Early) Release Frequency (LERF/LRF). In a MUPSA, it is necessary to consider multi-unit accidents either of a causal nature, in which a single-reactor accident may propagate to affect other units, or as a result of a common cause event that affects multiple units or radiological sources concurrently. This expansion of scope leads to essentially all the technical issues and challenges identified in Table 2. The increased scope of accidents to consider leads to a more complex definition and modelling of initiating events, accident sequences, end states and risk metrics. The remaining issues of treatment of dependencies in a PSA including; physical, functional and human dependencies, have become more difficult to address. Fortunately, there has been some experience in performing MUPSAs, and the efforts underway in Canada, the United States, other countries and the IAEA, as reflected in the workshop presentations, and offer guidance for the next efforts for completing and implementing them.

Table 1: Summary of MUPSA Status in Participating Countries and Organizations

Country/Organization	Current Status' of MUPSA
IAEA	• A draft safety report on a technical approach to multi-unit site PSA to be published in 2015 was made available by the IAEA to session chairs and workshop organizers from the CNSC and was widely discussed at the workshop, and additional guides are being developed to support treatment of external hazards in MUPSA. • A report on safety goals is being developed that addresses MUPSA issues was provided to workshop participants. • Existing PSA guides are being modified to address MUPSA issues (e.g., TECDOC-1511 on PSA attributes for PSA applications).
Organisation for Economic Co-operation and Development (OECD)/NEA WGRISK	• Task to address MUPSA issues under consideration, likely to be influenced by results of this workshop.
Canada	• Multi-unit interactions already included in existing reactor-unit PSAs because of extensive sharing of systems and use of common containment (vacuum building) • Recently modified regulatory requirements to address MUPSAs following Fukushima Daiichi accident • MUPSA pilot study planned • Both the CNSC and COG sponsored international workshops on MUPSA • Site-based safety goals under development
United States	• Historically, reactor-based risk metrics have been compared with safety goals for the entire site. • A two-unit Level 3 PSA on the Seabrook Station in 1983 attributed more than 14% of the single-unit CDF to multi-unit accidents. • Operating experience data have been analyzed for multi-unit insights; nearly 10% of the reviewed data indicate multi-unit effects. • MUPSAs completed for modular high-temperature reactor designs in 1990s. • Multi-unit insights from single-unit PSAs on sites with extensive sharing of systems. • USNRC is currently performing a two-unit Level 3 PSA on a U.S. operating plant, including spent fuel pool. • American Society of Mechanical Engineers (ASME)/American Nuclear Society (ANS) trial-use Probabilistic Risk Assessment (PRA) standard for advanced non-light water reactors (LWRs) includes

Country/Organization	Current Status' of MUPSA
	requirements for integrated multi-unit Level 3 PRA (December 2013).
United Kingdom	• Safety Assessment Principles (SAPs) have been clearly stated for multi-unit sites. • Multi-unit initiating events and interactions are explicitly considered against SAPs in evaluations. • Simple aggregation of reactor-based risk metrics have been used to compare with SAPs. • Costs and benefits of integrated MUPSAs currently being evaluated.
France	• Multi-unit events identified from service experience involving external flooding and loss of ultimate heat sink. • Identification of how the selection of initiating events and modelling of accident sequences for a PSA are affected by multi-unit considerations. • Evaluated loss-of-heat-sink events from deterministic and probabilistic perspective. • Current efforts underway to model the impact of loss-of- heat-sink events on multiple units.
Nordic countries (Finland, Sweden)	• Limited scope "other unit" and multi-unit station blackout PSAs being considered. • Current PSAs limited to single-unit accidents with shared system dependencies addressed. • Systematic MUPSAs under consideration as longer-term item. • Joint project for MUPSA being planned, to be guided by WGRISK actions.
Japan	• Multi-unit seismic PSA models being developed that address seismic fragility correlation for similar components at different locations on an NPP site. • Variations in seismic ground motion within an NPP site to same seismic event under investigation. • Identification of multi-unit and multi-site interactions during 2011 Great Japan Earthquake and Tsunami that pose challenges for MUPSAs. • Improved hazard models being developed for predicting the frequency of large tsunami events at specific NPP sites.
India	• Recognition of the need for site-based risk metrics and MUPSAs inspired by Fukushima Daiichi accident.

Table 2: Technical Issues and Challenges for Multi-unit site PSA

Technical area	Technical Issues and Challenges	Comments
MUPSA infrastructure	• Lack of experience and guidance for performing MUPSA; small body of existing case studies in MUPSA. • Lack of existing deterministic safety analyses of multi-unit accidents to support MUPSA. • Need to revisit and re-analyze the international operating experience for lessons to be learned from significant events and accidents for MUPSA insights; many examples of such events discussed at workshop.	• It is expected that experience in performing MUPSA will increase significantly in the coming years.
Selection of initiating events	• Many single-unit PSA-initiating events (e.g., loss of off-site power, loss of heat sink, external events) challenge multiple units. • Need to delineate single-unit/facility and multi-unit/facility events. • Most external events involve multi-unit challenges. • Extent of shared systems increases the importance of some internal initiating events (e.g., support system faults).	• All multi-unit NPP sites share a common electrical grid, ultimate heat and elements of the switchyard; some sites share common safety systems and structures. • Essentially, all external hazards challenge the entire site.
Accident sequence modelling	• Need to delineate single and multi-unit accident sequences. • Need to account for multi-unit common cause and causal dependencies, including functional, human and spatial dependencies; MUPSA models more than just a set of single-reactor PSA models. • Need to consider adverse impacts of single reactor/facility accident on other units, thus creating additional multi-unit accident scenarios. • Need to consider how operator actions may be adversely affected by multi-unit interactions. • Need to consider the timing of releases from different units. • Need to consider how radiological contamination of the site may inhibit operator actions and accident management measures. • Need to consider new end states involving multi-unit accidents and interactions, including the effects of combined and correlated hazards.	• Most single-unit PSAs assume that the other reactor units and radiological sources are safe in modelling single-unit accident sequences. • Deterministic safety analyses are also largely confined to single-unit accidents • An accident on one unit could trigger an

Technical area	Technical Issues and Challenges	Comments
	• Problem of proliferation of multi-unit combinations for sites with three or more reactor units. • Limitations of static PSA modelling approaches may require a re-evaluation of dynamic PSA approaches.	accident sequence on one or more additional units.
Accident sequence quantification and site-based risk metrics	• Need for additional risk metrics beyond CDF and LERF to fully express the risk profile of a multi-unit site. • Need to change frequency basis from events per reactor year to events per site year to capture risks from non-reactor sources and multi-unit accidents. • Lack of surrogate frequency-based risk metrics for spent fuel accidents; temporal variations in the radiological hazard in spent fuel storage. • Need to delineate CCF models and supporting data analysis to address inter-unit and intra-unit CCFs. • Need to improve human reliability models and analyses to address performance-shaping factors unique to multi-unit accidents. • Need to rethink the selection of mission times and consider extending beyond 24 hours. • Need to address variations in site response to the same earthquake and correlation among component fragilities in the MUPSA context. • Current issues in single-reactor PSA with proliferation of scenarios, impact of conservatisms and difficulties in achieving realistic fire PSA results will be compounded in the multi-unit PSA context. • Current issues in single-reactor Level 2 PSA with treatment of human actions during implementation of Severe Accident Management Guidelines (SAMGs) and prioritization of emergency response measures will be even more difficult in the MUPSA context.	• Current frequency-based surrogate risk metrics for single-unit PSAs (e.g., CDF and LERF) were historically derived from results of Level 3 PSAs; need to rethink this link in the MUPSA context.
Accident progression and source term characterization	• Existing severe accident models that are limited to single-reactor accidents will have to be enhanced to treat multi-unit and fuel storage accidents • Need to define new release categories that adequately describe the releases from multi-unit accidents; this includes release magnitudes, energies, and timing from reactor units, spent fuel storage and other radiological sources	• Plants with shared safety systems and structures may respond differently to single- and multi-unit accident sequences.
Evaluation of	• Consequence models need to consider how to model releases from multi-unit	• There are many

Technical area	Technical Issues and Challenges	Comments
radiological consequences	and multi-facility accidents; this includes consideration of different points of release from the plant, possible differences in time of release and release energies for plume rise considerations. • Method of decoupling consequence models from inventories needs revision for spent fuel accidents.	sources of non-linearity when estimating the radiological consequences from multi-unit and multi-source accidents. • Simple scaling of results from single-unit PSAs is fraught with pitfalls.
Site-based safety goals, risk integration and interpretation	• Method of aggregating risk contributions across different reactor units and facilities, single- and multi-unit and facility accidents, hazard groups and operating states with due regard to differences in level of realism/conservatism, level of detail in modelling, and uncertainty treatment. • Methods for comparing calculated risks against existing and new site-based safety goals. • Question of whether safety goals should be quantitative or qualitative, supported by quantitative safety design objectives. • Lack of multi-unit site-based acceptance criteria for evaluating the integrated risks from a multi-unit site PSA. • Need for more international consensus on approach to safety goals and use of such goals to interpret PSA results.	• Current risk acceptance and risk significance criteria largely based on reactor-based risk metrics such as CDF and LERF. • Difficulty in communicating risk information from piecemeal risk studies to assure that safety goals have been achieved.

2.4 Path forward in MUPSA

Workshop presentations and discussions provide a snapshot of what can be expected in the future to aid in the advancement of MUPSA and site safety goal development. This upcoming progress in MUPSA is expected to be received from the following sources:

- The IAEA is expected to publish a series of safety reports on a technical approach for multi-unit site PSA and the guidance needed to address the various external hazards that need to be considered.
- A pilot study is planned for a multi-unit site in Canada that will address the integrated risks from a spectrum of internal and external hazards and plant operating states and will examine the use of site-based risk metrics.
- A Level 3 PSA research project is currently underway at the USNRC for the two operating pressurized water reactors at the Vogtle Electric Generating Plant. The PSA will address multi-unit accidents, as well as accidents involving the spent fuel storage pools.
- A multi-unit (two-unit) PSA is being developed for the high temperature pebble bed modular reactor that is currently under construction in China. A site-based metric and acceptance criterion has been selected and agreed upon by the Chinese regulatory authority. The frequency of an accident involving one or both reactors that produces a site boundary dose exceeding 50 millisieverts must be kept below 1×10^{-6} per site year according to this criterion. This PSA is being performed as a pilot study for the ASME/ANS PRA standard for advanced non-LWRs, which includes requirements for MUPSAs.
- The IAEA has a framework for the development of safety goals in IAEA member states. This framework provides an excellent opportunity to develop an international consensus on a hierarchical approach for development of both qualitative safety goals and quantitative safety design objectives that account for MUPSA and site-based considerations, as well as the important challenge of communicating safety and risk information to the public.
- There was general consensus expressed at the workshop that more work needs to be performed to collect, review and analyze insights from reactor operating experience with events, incidents and accidents at multi-unit sites.
- Under a University of Maryland and USNRC cooperative agreement, a formal assessment of the current USNRC safety goals in the context of multi-unit site risk will be performed. The study is expected to discuss the options to define and assess surrogate risk measures of CDF, LRF and LERF related to the total site risk and to determine whether the corresponding quantitative health objectives will be met.

As a result of these many activities, it would be prudent to consider a future workshop in approximately two years to capture the advancements in the technology of MUPSA and implementation of site safety goals. In moving forward to upgrade existing single-unit PSA to

address multi-unit risks, it was suggested that priority be given to the treatment of loss of offsite power and station blackout events, to which all multi-unit sites are susceptible. Another key area is to expand the current CCF models to differentiate between those that affect single units and those that affect multiple ones. Spent fuel storage accidents, which are often excluded from single-unit PSAs, need to be considered for both single-unit and MUPSAs.

3. Summary of Workshop Presentations and Discussions

3.1 Opening Session

The opening session of the workshop was conducted the morning of November 17, 2014, and was comprised of eight presentations that framed the topics and challenges for the workshop as a whole. The speakers and presentation topics for this session are listed in Table 3.

Yolande Akl, CNSC Director of the Probabilistic Safety Assessment and Reliability Division, kicked off the session by summarizing the workshop program and the objectives that had been set by the CNSC in preparation for the workshop. Michael Binder, CNSC President, provided his vision for a successful workshop in building an international consensus on the approaches to be taken to address the integrated risks at multi-unit sites and communicating these risks to the public with the use of site safety goals. In a presentation by Gerry Frappier, CNSC Director General, Directorate of Assessment and Analysis, workshop participants were given an excellent introduction to the CNSC's Risk Informed Decision Making (RIDM) process and key steps taken to address the lessons learned from the Fukushima Daiichi accident. Afterwards, Co-Chair Marina Röwekamp provided an OECD/NEA WGRISK perspective and expectations for MUPSA and site safety goals.

George Apostolakis, former USNRC Commissioner and Professor Emeritus at MIT, summarized the U.S. actions in addressing multi-unit risk issues following the accident at Fukushima Daiichi. He also identified challenges to MUPSA and site-based safety goals that were extensively discussed and debated in the remaining sessions of the workshop.

Following this, Kenta Hibino of the IAEA, summarized activities underway at the IAEA that were relevant to the workshop topics, and these included the development of a series of safety reports that offer guidance in the performance of a MUPSA. This was also a specific topic for several presentations in the subsequent technical sessions. After the IAEA summary, Fred Dermarkar, President of COG, provided a history of PSA in Canada noting that PSA methodologies have long incorporated multi-unit aspects. Looking ahead, he highlighted the need to develop complementary methods to take human resilience in accident response into consideration, particularly for extreme events where traditional Human Reliability Analysis (HRA) methods might not be as well suited. A risk informed perspective on these issues would

be incomplete without addressing the implications of multi-unit accidents on defence-in-depth, as eloquently expressed by Greg Rzentkowski, CNSC Director General, Directorate of Power Reactor Regulation. Thus, the opening session prepared the way for more detailed technical discussions that framed the subsequent technical sessions. As with all the sessions, they proved to be excellent technical discussions and interactions between workshop participants and the session speakers.

Table 3: Presentations and Speakers for Opening Session

Time	Title/Author	Organization	Country
9:30–9:40	**Welcome address by workshop chairperson** Yolande Akl Director, Probabilistic Safety Assessment & Reliability Division (PSA&RD)	CNSC	Canada
9:40–9:50	**Opening remarks** Michael Binder President, Canadian Nuclear Safety Commission	CNSC	Canada
9:50–10:00	**Workshop address** Gerry Frappier Director General, Technical Support Branch	CNSC	Canada
10:00–10:20	**Keynote speech** Marina Röwekamp Chair, OECD/NEA WGRISK, GRS	GRS, OECD/NEA	Germany
10:20–10:50	*Break and networking*	-	-
10:50–11:20	**Keynote speech by Workshop Technical Advisor** George Apostolakis Former U.S. NRC Commissioner, Professor Emeritus at MIT, Head of Nuclear Risk Research Center	MIT & Nuclear Risk Research Center	United States & Japan
11:20–11:40	**Introduction of ISSC-EBP WA8 Activity "External Events Safety Assessment of Multi-Unit Sites"** Kenta Hibino	IAEA/ISSC	-

Time	Title/Author	Organization	Country
11:40–12:10	**Looking Back Upon Canadian Multi-Unit PSA Experience, and Looking Ahead Using Fukushima Daiichi and Daini Lessons Learned** Fred Dermarkar President and CEO, CANDU Owners Group	COG	Canada
12:10–12:40	**Risk-Informing Reactor Defence-in-Depth Concept** Greg Rzentkowski Director General, Directorate of Power Reactor Regulation	CNSC	Canada

3.2 Technical Session 1: Selection of Risk Metrics for Multi-unit sites

The afternoon of November 17, 2014, was devoted to the first of several technical sessions that made up the workshop. Session 1 was dedicated to the topic of risk metrics for PSAs on multi-unit sites and the associated issue of risk aggregation for full scope PSAs that cover a spectrum of internal and external events and hazards. The speakers and presentation topics for this session are listed in Table 4.

Collectively, the presentations and subsequent discussions inspired by these questions focused on the following key issues:

- Are current safety goals adequate, and can they address multi-unit risks? Should there be additional goals? Societal disruption goals? Relative or absolute?
- Should the safety goals be linked to site-based or reactor-based risk metrics?
- Should previous risk-informed decisions based on single-unit risk metrics be reviewed in light of multi-unit risk issues?
- What criteria should be used to evaluate the use of shared systems?
- How can deterministic safety evaluation of multi-unit events be strengthened?

As a result of the presentations and subsequent discussions, there appeared to be a consensus on the following key points:

- MUPSA analysis is important. Single-unit PSAs for reactors on multi-unit sites are incomplete, as the risks of accidents involving multiple units or radiological sources are obscured in single-unit risk metrics. Site-based risk metrics are needed to augment reactor-based risk metrics in order to more fully capture the integrated risks to which the public is exposed.
- Level 3 PSAs that include quantification of radiological exposures to the public are important to retain within the scope of MUPSAs. These PSAs need further

consideration until there is a sufficient body of work from which to define and calibrate surrogate risk metrics such as CDF and LERF. Numerical objectives for reactor-based metrics such as CDF and LERF were supported by a body of work from Level 3 PSAs on single-reactor units. Insights from site Level 3 PSAs and supporting radiological consequence analyses are necessary for establishing suitable design objectives for site CDF and site LERF-type metrics.

- Canadian efforts in developing safety goals and metrics for multi-unit sites are notable. Canada is ahead of other countries in tackling multi-unit considerations in PSAs and in formulating whole-site safety goals.

In addition to these points of general agreement, there was a productive discussion, but no consensus reached on the following:

- A number of different site-based risk metrics were presented from the IAEA work and from the CNSC and COG. Site-based metrics bring out risk insights not available with reactor-based metrics. Additional work is needed to resolve how site-based metrics can be used in concert with reactor-based metrics to support risk-informed decision making. Multi-unit risk should be used for identifying important site risk contributors. However, some believed that safety goals should be kept at the unit level.
- Implications of using a site-wide PSA as a methodology to learn key features of multi-unit risk were discussed. It was noted that such a methodology for deterministic analysis of multiple units does not exist. Existing definitions of defence-in-depth used at the IAEA and the USNRC do not explicitly address the potential for and need to prevent and mitigate multi-unit accidents. Multi-unit risk insights can be used to enhance the implementation of defence-in-depth principles and to consider whether current regulatory requirements regarding shared systems and structures are adequate in light of the potential for multi-unit accidents.
- Increased consideration of societal disruption as an important multi-unit safety goal parameter was discussed. There were some choices and options to quantify it. However, no consensus on which metrics are relevant seemed to appear, and more research would be needed at this point. Could there be an approach to formally address security risk in the context of the traditional PSA? There were multiple viewpoints expressed, and some believed that PSA is not well suited for this purpose. However, others were of the opinion that PSA techniques are useful in evaluating security risks.

Table 4: Presentations and Speakers for Technical Session 1

Time	Title/Author	Organization	Country
14:00–14:05	**Introduction of co-chairs** **Introduction of the thematic topic by the co-chairs** Karl Fleming (KNF Consulting Services) Mohammad Modarres (University of Maryland)	KNF Consulting Services & University of Maryland	United States
14:05–14:30	**Site-Based Risk Metrics for Multi-Unit PSA** Karl Fleming	KNF Consulting Services	United States
14:30–14:55	**Proposed Site-Based Safety Goals for CANDU Stations** Jack Vecchiarelli Manager, Nuclear Safety & Technology Dept. Ontario Power Generation (OPG)	OPG	Canada
14:55–15:20	**Risk Aggregation and Integration Methods** Smain Yalaoui, Technical Specialist	CNSC	Canada
15:20–15:50	*Break and networking*	-	-
15:50–16:15	**Significance of Multi-Unit Nuclear Plant Risks and Implications of the Site-Level Quantitative Health Objectives** Mohammad Modarres	University of Maryland	United States
16:15–16:40	**Risk Aggregation Principles** Ben Hryciw	AMEC NSS	Canada
16:40–17:40	**Guided discussion led by Co-chairs**	-	-

3.3 Technical Session 2: Role of Site Safety Goals in the Licensing Process

This technical session consisted of five presentations given by regulators from Canada (CNSC), the United States (USNRC) and Sweden (Swedish Radiation Safety Authority [SSM]), along with one presentation from the Canadian industry (COG) and one presentation from the Nuclear Energy Institute (NEI). The speakers and presentation topics for this session are listed in Table 5. The presentations covered specific subjects that could be grouped under:

- Safety goals,
- Integrated site risk metrics,
- Surrogate measures,
- Application of PSA and safety goals,
- Alignment activities.

The presentations and the discussions showed that there are common activities underway internationally to advance understanding and regulation of multi-unit risks.

Generally, there appears to be a trend towards safety goals being developed in a hierarchical structure, from qualitative high levels, rooted in legislation, to more quantitative, surrogate safety goals, sometimes referred to as safety design objectives (e.g., CDF, LRF), at the bottom levels. A common theme was that safety goals should consider both the adverse health effects and the societal disruptions caused by a nuclear accident. Regarding the different treatment of the safety goals for existing and new reactors, a question was raised about goal stability for the same technology. Continuous improvements need to be conveyed to the public by projecting the stability over time of what is considered safe enough. This translates to keeping the qualitative objectives stable.

During discussions, participants brought up the topic of risk communication and possible solutions for improvement. In communicating risk, one has to be aware there are three groups of the public: (1) supporters, (2) neutral parties and (3) opponents of nuclear energy. Regardless of the public group, we need to be open and transparent in order to gain their confidence, as accidents undermine the credibility of the industry and the regulators. On the same subject of risk communication, a suggestion was made to invite experts in communication to work with PSA practitioners to help them to understand how to better communicate.

The dependence of the surrogate metrics on the site (i.e., in relation to proximity to large population centres) is another subject that requires further discussion. In addition, surrogate metrics for onsite non-reactor sources, such as spent fuel pools, need to be addressed.

On the concept of "practical elimination" of potential accident sequences, there were questions about its meaning and its practical implementation, as well as about the concept's application to both surrogate safety goals, LRF and CDF. This is another area for further exploration.

With respect to the USNRC pilot application of Level 3 PRA, there were challenges in identifying the integrated site risk metrics that measure multi-source effects and in quantifying multi-source accident sequences involving release paths from one or more sources.

The demonstration of the relationship between the surrogate metrics (e.g., CDF, LRF) and the upper-level objectives remains a subject that needs to be clearly defined. Another important aspect relates to the use of the surrogate metrics as "targets" versus "limits," with a proposal for elimination of the term "limit" as applied to PSA results. While it is still early to claim consensus, an interesting outcome from the presentations and discussions was a trend towards the use of individual-unit CDF and whole-site LRF.

On the application of PSA and safety goals, the use of PSA results rather than numbers to gain insights, as well as the role of safety goals rather than measures as indicators were discussed. There were also questions on how to use PSA and safety goals to guide the scope of deterministic safety analysis, and how to adapt current regulatory risk-informed methods from a unit basis to a site basis.

Finally, several activities currently underway include:

- CNSC Working Group on Safety Goals,
- COG Project on Whole-Site PSA,
- U.S. Risk-Informed Steering Committee,
  - industry and USNRC on the committee,
  - supported by the NEI and the Electric Power Research Institute (EPRI),
- SSM PSA group's bilateral agreements for cooperation with the PSA groups at Finnish Radiation and Nuclear Safety, the USNRC and the CNSC.

In conclusion, the session and discussions revealed commonalities and trends in approaches for the development and use of safety goals, as well as challenges and areas that need further attention.

Table 5: Presentation and Speakers for Technical Session 2

Time	Title/author	Organization	Country
8:30–8:35	**Introduction of co-chairs** **Introduction of the thematic topic by the co-chairs** Raducu Gheorghe, Technical Specialist (CNSC) Fred Dermarkar (COG)	CNSC & COG	Canada
8:35–9:00	**Development of the Canadian Regulatory Safety Goals for Multi-Unit NPP sites** Raducu Gheorghe	CNSC	Canada
9:00–9:25	**U.S. Industry Efforts to Improve Treatment of Uncertainty in Risk-Informed Decision Making** Victoria Anderson	NEI	United States
9:25–9:50	**U.S. NRC Site Level 3 PRA Project – Integrated Site Risk and Challenges for Risk-Informed Decision-Making** Margaret Tobin/Daniel Hudson	USNRC	United States
9:50–10:20	*Break and networking*	-	-
10:20–10:45	**Swedish Legislation on Multi-Unit Risks and PSA Activities** Ralph Nyman	SSM	Sweden
10:45–11:10	**On the Concept of a Hierarchal Safety Goals Framework** Jack Vecchiarelli	OPG	Canada
11:10–12:10	**Guided discussion led by Co-chairs**	-	-

3.4 Technical Session 3: Experience with MUPSA (part 1)

During the session, there was a presentation on the IAEA technical approach to meet the challenges in MUPSA, and to develop guidance for expanding the scope of PSAs to include the integrated risks of multi-unit sites. The presentation aimed to define appropriate risk metrics for site safety assessments and to identify initiating events that affect more than one reactor unit or nuclear facility, including those due to single hazards and combinations of hazards. Treatment of CCFs on multi-unit sites that distinguish between events that affect a single-reactor unit or nuclear facility and those that affect components in different units was highlighted as a key issue. The speakers and presentation topics for this session are listed in Table 6.

During the guided discussions, the participants were asked to elaborate on the statement made by Karl Fleming: "Addressing multi-unit risk is not a state-of-the-art limitation, but rather a weakness in the state-of-the-practice." The general understanding is that the current PSA state-of the-art forms the basis for conducting a MUPSA, provided that the challenges are well identified and addressed. These include:

- Resolution of the impact of CCFs on single versus multiple units,
- Consideration of HRA in MUPSA,
- Other issues and challenges summarized in Table 2 of this report.

While it was acknowledged during the discussion that MUPSA poses some unique challenges, such challenges are not the reason there has been such little emphasis on including multi-unit accidents in previous PSAs. The principal reason was the assumption, now open to question, that the risks of multi-unit sites could be adequately managed by examining each reactor unit through the lens of a single-reactor PSA model. The presentation by Yugi Kamagai from the Tokyo Electric Power Company (TEPCO) highlighted the many multi-unit interactions that were evident during the Fukushima Daiichi accident and are not included in most single-unit PSAs. From all this evidence, it was suggested that the single-reactor mindset in nuclear safety evaluations needs to be replaced by a site-based perspective.

The session also included two presentations on the analysis of multi-unit accident progression in CANDU reactors using the Modular Accident Analysis Program (MAAP)-CANDU to support the Level 2 PSA. It was mentioned that the current MAAP-CANDU code can only explicitly simulate a single-reactor core during a simulation, and this limitation affects simulations in which more than one unit undergoes an accident. The two presentations discussed the different approaches such as: containment scaling, injection method and accident simulation method.

Regarding the consequence analysis for multi-unit stations, the participants discussed the issues related to the consideration of different release timing and duration, releases from different locations at the site, and uncertainties in release timing and weather conditions. The overall link between release attributes and the safety goals needs further consideration.

Table 6: Presentations and Speakers for Technical Session 3 (part 1)

Time	Title/Author	Organization	Country
13:30–13:35	**Introduction of Co-chairs** **Introduction of the thematic topic by the Co-chairs** Karl Fleming (KNF Consulting Services) Smain Yalaoui (CNSC)	KNF Consulting Services & CNSC	United States & Canada
13:35–14:00	**IAEA Technical Approach to Meeting Challenges in Multi-Unit PSA** Karl Fleming	KNF Consulting Services	United States
14:00–14:25	**A Methodology for Performing Consequence Analysis for Multi-Unit/Spent-Fuel-Pool Source Terms** Nathan E. Bixler	Sandia National Laboratories	United States
14:25–14:50	**Important Multi-Unit Interactions During Fukushima-Daiichi Accident** Yuji Kumagai	TEPCO	Japan
14:50–15:20	*Break and networking*		
15:20–15:45	**Multi-Unit Modelling with MAAP-CANDU** John Kennedy	AMEC NSS	Canada
15:45–16:10	**Development of a Multi-Unit Severe Accident Software Simulator Using MAAP-CANDU** Tom Elicson	Erin Engineering	United States
16:10–17:10	**Guided discussion led by Co-chairs**	-	-

3.5 Technical Session 3: Experience with MUPSA (part 2)

During this session, the experiences of each member state were demonstrated and shared with workshop participants. There were five presentations: two from Japan, one from France and two from the United Kingdom. The speakers and presentation topics for this session are listed in Table 7.

The first presentation focused on the characteristics of earthquake hazards and on lessons learned from the recent events at the Fukushima and Kashiwazaki-Kariwa NPPs in Japan, and considered the spatial correlation of earthquake ground motions at nuclear plant sites. The following conclusions were reached: For a multi-unit site, the seismic ground motion for each unit is very similar if the site ground structure has little irregularity. Seismic safety of the multi-unit plant should be estimated on the basis of the assumption that the same ground motion is applied to all units. If the ground structure is complex and significantly irregular, however, the characteristics of ground motion for each unit may be so different that the complexity and irregularity should be properly modelled to estimate ground motions. A newly proposed macro-spatial ground motion correlation model can be utilized effectively to estimate the spatial correlation of ground motions in a wide region surrounding an NPP site.

The second presentation introduced a multi-unit Level 1 seismic PSA model developed by the Japanese Nuclear Regulation Authority in light of the Kashiwazaki-Kariwa event of 2007, in which seven boiling water reactor units on the site were struck by a severe earthquake. As an example, the multi-unit seismic PSA model for twin units based on the security communications (SECOM)-II codes was shown. Seismic responses and capacities of the Structures, Systems and Components (SSCs) of the two model units were provided as a function of the correlation coefficients between SSCs.

The third presentation, based on operating experience in France, showed that external hazards have the potential to cause initiating events and simultaneously impair safety systems. Some examples are the partial flooding of the Blayais NPP in December 1999, the ice formation on the grid transformers at the Paluel site in 2005, the total loss of the heat sink at Cruas units 3 and 4 in 2009, and the partial loss of heat sink at Fessenheim unit 2 in 2009. In this context, in France, both the operator, Électricité de France (EDF), and the Institut de Radioprotection et de Sûreté Nucléaire (IRSN), in addition to reviewing deterministic bases and studies on external events, work on probabilistic aspects related to external-event PSA (hazards screening analysis, SSC fragility assessment, HRA, etc.). They also work to improve methods to better take into account in the PSA the long term of accident sequences induced by initiators that may affect the whole site containing several nuclear installations (reactors, fuel pools, etc.).

The fourth and fifth presentations explained current practices and the safety goal framework in the United Kingdom. They included a presentation that briefly described how PSAs are used in the United Kingdom to support design, licensing and operation of NPPs and how this relates to safety goals and risk-informed decision making. Issues associated with multi-unit/multi-facility PSAs were also addressed. The presentation concluded that, although the emphasis on the use of PSA has been on the insights into and the understanding of the plant design and performance, safety goals are fundamental to the coherent use of analysis in decision making. The basic aim is to protect the public and, from that point of view, what matters is the risk posed by the site as a whole. Challenges posed by site PSAs include the following: site goals best expressed in terms of radiological releases or doses outside the site, facilities/units normally designed individually using lower level goals, and accounting for dependencies.

After these presentations, the participants addressed and extensively discussed:

- The importance of correlations under seismic situations:
  - different acceleration records at different units and impact on the seismic PSA,
  - seismic correlation importance in the evaluation of CDF and LRF,
  - effect of offsite facility (e.g., transmission line) failure on NPPs under external hazards,
  - a more elaborated mechanistic model to take account of correlated response of SSC (e.g., IAEA document).
- Need for essential initiating events:
  - loss of offsite power, which is the greatest contributor to CDF,
  - incorporation of loss of offsite power into MUPSA,
  - loss of ultimate heat sink due to offsite events.
- Need for data collection:
  - data collection of correlation characteristics,
  - collection and translation of experience data from all countries (NEA, OECD, USNRC, others).
- Other issues:
  - licensing process of siting multi-unit facilities,
  - consideration of HRA,
  - advantage of PSA for communication with the public,
  - design criteria in deterministic analyses and PSA,
  - development of mechanistic model for external floods, etc.

The participants fully agreed that response correlation or failure correlation within a single unit, as well as among multiple units under external hazards such as earthquakes, should be properly taken into consideration in a PSA implementation, and that further research on the correlation is needed.

The participants also noted the importance of sharing operating experience data and operational insights from multi-unit events as a basis for building MUPSA. There are many ongoing international efforts that need to be coordinated to serve as a basis for MUPSA. Work is being performed by the OECD/NEA WGRISK, ASMPSA (Europe), FIRE database, Accident Sequence Precursor Program (USNRC), International Event Analysis Meeting, and the International Common Cause Failure Database Exchange (ICDE). It was brought to the attention of the participants that the ICDE Steering Committee will be holding a workshop on failure analysis of CCF events that have an impact on multi-unit NPPs.

Table 7: Presentations and Speakers for Technical Session 3 (part 2)

Time	Title/Author	Organization	Country
8:30–8:35	**Introduction of Co-chairs Introduction of the thematic topic by the Co-chairs** Tsuyoshi Takada (University of Tokyo) Smain Yalaoui (CNSC)	University of Tokyo & CNSC	Japan & Canada
8:35–9:00	**Spatial Variation of Earthquake Ground Motions for Multi-Unit Site** Tsuyoshi Takada	University of Tokyo	Japan
9:00– 9:25	**Development of Multi-Unit Level-1 Seismic PRA Model** Keisuke Kondo	Secretariat of Nuclear Regulation Authority	Japan
9:25–9:50	**Comprehensive PSA Modelling of Loss of Heat Sink Events** Patricia Dupuy	IRSN	France
9:50–10:20	*Break and networking*	-	-
10:20–10:45	**Current UK Practice on Integrated and Multi-Unit PSA** Bert Commandeur	Jacobsen Analytics	United Kingdom
10:45–11:10	**Safety Goals and Multi-Unit PSAs – What Are We Trying to Achieve?**	EDF Energy	United Kingdom

Time	Title/Author	Organization	Country
	Nigel Buttery		
11:10–12:10	**Guided discussion led by co-chairs**	-	-

3.6 Technical Session 3: Experience with MUPSAs (part 3)

The first presentation included information on efforts by IRSN (France) related to the development of a PSA for multi-unit sites. The main steps of this development are analysis of internationally available information, identification of important aspects to be treated in MUPSA and analysis of available operating experience.

The second presentation referred to the CNSC study in response to the Commission's request for staff to assess health and environmental consequences of severe accident scenarios. This study was to address concerns raised during public hearings and the environmental assessment of the refurbishment and continued operation of the Darlington Nuclear Generating Station (DNGS). The study identified a generic source term based on the LRF defined in REGDOC 2.5.2, *Design of Reactor Facilities: Nuclear Power Plants* (10^{14} Becquerel's of Cs-137). Then the doses with and without protective actions (in Ontario) were estimated. The considered cancers on receptors were for adult male and child female (thyroid).

The third presentation included background information on multi-unit sites in Canada, as well as design specificities of CANDU sites. It should be noted that there is a high degree of sharing systems between the units (safety and support systems). The Darlington Probabilistic Safety Evaluation (DPSE) study and post-DPSE studies (Bruce and Pickering stations) were then presented. These studies cover Level 1, 2 and 3 PSAs for internal events (focused on power operation, the outage modelling being simplified) and treat multi-unit initiators, such as loss of offsite power, and initiators with multi-unit impacts, such as main steam line breaks.

The fourth presentation referred to the efforts of the Atomic Energy Regulatory Board (AERB-India) to develop MUPSA. The presentation highlighted that the simultaneous failures of systems and components at multiple nuclear plants in a site were earlier considered a rare event in PSA. The Fukushima accidents revealed the need for multi-unit safety assessment and safety goals, procedures and guidelines to achieve and maintain the basic safety goals of protecting the public and the environment.

The fifth presentation focused on the University of Maryland's (United States) efforts to develop approaches for MUPSA based on dynamic PSA methods. The motivation for these efforts is the increasing interest in MUPSA after the Fukushima accident, the IAEA Action Plan on Nuclear Safety and the ongoing USNRC project on Level 3. A review of the state of the practice regarding the multi-unit risk assessment was presented. (Nuclear reactor regulation is focused on single units; multi-unit site risk is not formally considered; and the risk metrics CDF and LRF do not capture the integrated site risk.)

The sixth presentation, by the CNSC (Canada), focused on regulatory experience from the existing multi-unit facilities in Canada and discussed future possible solutions: new multi-unit NPPs or Small Modular Reactors (SMRs). In Canada, a licence is issued for all activities concerned with a facility regardless of the number of units. If differences exist between units, they are reflected in the licensee's licensing basis documents. For CANDU stations, shared systems were designed to supplement unit-specific defence-in-depth, following a station-wide approach to safety.

For the guided discussion, several important subjects related to the presentations and following clarifying questions were identified, including:

- Operating experience from multi-unit sites (occurrence and mitigation of multiple initiating events),
- Use of PSA for multi-unit site safety,
- Consequence analysis,
- Lessons learned from MUPSA modelling,
- Open questions.

The speakers and presentation topics for this session are listed in Table 8.

Operating Experience from Multi-unit Sites (occurrence and mitigation of multiple initiating events)

Several aspects highlighted by some participants who had performed qualitative analysis of operating experience included:

- Direct impact of external hazards on site units,
- shared vulnerabilities in case of external hazards between site unit CCFs and/or between unit components,
- Failures or unavailability of unit shared systems,
- Cascading events from one unit to the other units,
- Site organizational aspects.

The discussions suggested that a better and more systematic analysis of the worldwide operating experience will be highly valuable in order to identify important aspects to consider for multi-unit site risk assessments. This analysis has to address the risk impact of various events as well. An international context will be preferable. Finally, it was proposed to include this subject, at least in limited manner, as part of the future CAPS on MUPSA that will be proposed for WGRISK consideration.

Use of PSA for Multi-unit Site Safety

Possible uses of PSA for multi-unit site safety evaluation were discussed. These include:

- Risk quantification,
- Assessment of new designs (e.g., SMRs),
- Identification of important site "shared" vulnerabilities in case of external hazards,
- Assessment of sufficiency of site equipment and resources,
- Assessment of sufficiency of accident guidance,
- Identification of mitigation strategies,
- Assessment of pros and cons of sharing systems and resources between site units.

The discussion concluded that the single-unit PSA, including the site aspects, may be sufficient for uses related to CDF (quantification or evaluation of some important site safety aspects for the prevention of core damage), but may not be enough if the release frequency is involved. The subject may need more investigation and may be related to the definition of site safety objectives.

Consequence Analysis

The discussions on consequence analysis focused on the conclusions of the CNSC study in response to the Commission's request for staff to assess health and environmental consequences of severe accident scenarios of the DNGS. The relevance of this study for the definition of site safety criteria was also discussed (doses, fatalities, number of cancers and type of cancers).

Lessons Learned from MUPSAs

The discussion on the lessons learned from MUPSA referred to the Canadian PSA for CANDU stations, which included the site aspects from the beginning (single-unit PSA that integrates site aspects: shared systems and components, multi-unit initiating events and unit initiating events affecting other units). The studies showed that multi-unit events dominate the risk. The interpretation of results and the assessment of the uncertainties may be different from the single-unit PSA. The need for an acceptable framework for Emergency Mitigating Equipment (EME) credit and SAMG guidance in PSA was expressed. This subject may need further discussion. Other methods to develop a MUPSA, such as a dynamic PSA, were discussed along with the

need for a holistic approach. The conclusion of the discussions was that, for the development of future MUPSAs, the lessons learned from the existing MUPSA should be considered. The methods and models should be simple enough to be traceable and applicable. It is also important to note that the PSA modelling is a function of its intended use. The need for a glossary was also expressed, since in different presentations different words were used for similar concepts.

Open Questions

The key open questions that came out in the discussions included the need to reconsider the adequacy of staffing to be able to cope with multi-unit events, the consideration of organizational factors and the prioritization of MUPSA developments. Regarding the organizational factors, it was stated that the current methods do not include organizational factors. Nevertheless, this aspect may be highly important for MUPSAs. Further research may be needed on this subject, which is also an issue for single-unit PSA. Regarding the priority of development of a MUPSA, the discussion referred to the assessment of "non-extreme" events having the potential to affect more than one unit over the assessment of "extreme" events. The conclusion was that the highest priority may be the study of multi-unit loss-of-offsite-power events and of the inter-unit CCF. The consideration of events affecting the reactor and the spent fuel pool may also become a priority.

Session Conclusions

The following are key conclusions from the session and the discussions that were inspired by them:

- A systematic analysis of the worldwide operating experience will be highly valuable in order to identify important aspects to consider for the multi-unit site risk assessment. This analysis has to address the risk impact of various events as well. An international context will be preferable. It was proposed to include this subject, at least in a limited manner, as part of the future CAPS on MUPSA that will be proposed for WGRISK consideration.
- The single-unit PSA, including the site aspects, may be sufficient for uses related to CDF (quantification or evaluation of some important site safety aspects for the prevention of core damage), but may not be enough if a release frequency assessment is performed. The subject may need more investigation and may be related to the definition of site safety objectives.
- For the development of future MUPSAs, the lessons learned from the existing MUPSA should be considered. The need for an acceptable framework for EME credit and SAMG guidance in PSA was expressed. This subject may need further discussion. The need for a holistic approach was also highlighted. The methods and

models should be simple enough to be traceable and applicable. It is also important to note that the PSA modelling is a function of its intended uses. The establishment of a common international glossary on MUPSA was also suggested.

- Regarding organizational factors, it was stated that the current methods do not model them in the PSA. Nevertheless, this aspect may be highly important for the MUPSA and should be taken into account, even if not explicitly. Further discussion may be needed on this subject. There was a suggestion to change the term "organizational factors" to "human performance", in order to avoid confusion.
- The first steps in the next phase of development of MUPSA may be the study of multi-unit loss- of-offsite-power events and the resolution of CCF treatment for both intra-unit and inter-unit effects. Events affecting the reactor and the spent fuel pool should also be given more consideration.

Table 8: Presentations and Speakers for Technical Session 3 (part 3)

Time	Title/Author	Organization	Country
13:30–13:35	**Introduction of Co-chairs** **Introduction of the thematic topic by the Co-chairs** Raducu Gheorghe (CNSC) Gabriel Georgescu (IRSN)	CNSC & IRSN	Canada & France
13:35–14:00	**Role of PSA in the Understanding of Progression of Events Affecting Multi-Unit Sites** Gabriel Georgescu	IRSN	France
14:00–14:25	**An Overview of CNSC's Study of the Consequences of a Hypothetical Severe Nuclear Accident and Effectiveness of Mitigation Measures** Andrew McAllister and Melanie Rickard	CNSC	Canada
14:25–14:50	**Development of Multi-Unit PRA Modelling in Canada** Eliseo Chan	Bruce Power	Canada
14:50–15:20	*Break and networking*	-	-

Time	Title/Author	Organization	Country
15:20–15:45	**An Approach for Risk Assessment at Multi-Unit NPP sites** C. Senthil Kumar	AERB	India
15:45–16:10	**Framework for Assessing Integrated Nuclear Power Plant Site Risk using Dynamic Probabilistic Assessment** Matthew Dennis	University of Maryland	United States
16:10–16:35	**Applying past Multi-Unit Operational Experience to Future Multi-Unit Technologies and Activities – Canadian Lessons Learned** Doug Miller	CNSC	Canada
16:35–17:35	**Guided discussion led by Co-chairs**	-	-

3.7 Technical Session 4: Challenges in MUPSA

The main common challenge for MUPSA found in all presentations of session 4 is the adequate consideration of human factors in the case of extreme events affecting the whole site. The speakers and presentation topics for this session are listed in Table 9.

The non-negligible effect of human performance on the whole event sequence has been recognized. The need to appropriately address it in the PSA, in particular in view of actions to be taken for event sequences affecting more than one reactor unit, has been identified.

Since methods considering human actions under extreme environmental and boundary conditions are lacking in PSAs performed to date, further R&D is needed. At present, no quantitative values for human error rates under extreme conditions – either target values or results from analyses – can be provided. However, the existing methodological approaches can be used for analyses of sensitive parameters including human error probabilities. In this context, learning from operating experience is essential for developing a suitable probabilistic framework for addressing multi-unit issues in safety assessment.

The guided discussion portion, being the last technical session in the workshop, was intended to reach some consensus on where the PSA community currently stands and what major challenges

remain, and what can be expected in the short term (one to three years) and long term (three years and beyond). There is a general consensus that the current effort in addressing MUPSA needs to continue. A follow-up workshop in approximately two years would be helpful.

Key challenges mentioned were the maturity of PSA methods in complex hazards (e.g., seismic events, high winds, external flood and fire); treatment of human performance; and effective communication of risk to the public through the use of an acceptable site-based safety goal framework.

Table 9: Presentations and Speakers for Technical Session 4

Time	Title/Author	Organization	Country
8:30–8:35	**Introduction of Co-chairs** **Introduction of the thematic topic by the Co-chairs** Eliseo Chan (Bruce Power) Marina Röwekamp (Chair, OECD/NEA, WGRISK and GRS)	Bruce Power & OECD/NEA WGRISK, GRS	Canada & Germany
8:35–9:00	**Technical Challenges in Multi-Unit Fire PSA** Nathan Siu	USNRC	United States
9:00–9:25	**Crediting Human Actions During Severe Accidents, Including Multi-Unit Considerations** Shawn St. Germain	INL	United States
9:25–9:50	**Human Reliability Challenges: Decision Making, Single and Multi-Units, and Performance-Shaping Factors** Jean-Yves Fiset	CNSC	Canada
9:50–10:15	**Relative Risk for Operating Multiple Facilities at Multiple Sites** Romney Duffey	DSM Associates Inc., Idaho	United States
10:15–10:45	*Break and networking*	-	-
10:40–11:45	**Guided discussion led by Co-chairs**	-	-

3.8 Plenary Session

A final plenary session was held in the afternoon of November 20, 2014, and provided an opportunity for the CNSC, former USNRC Commissioner Apostolakis and workshop organizers to thank all the participants, co-chairs and speakers, and to set the vision for the future development of MUPSA and the implementation of site safety goals. The speakers for this session are identified in Table 10. The main technical findings of the workshop are summarized in Section 2 of this report.

Ramzi Jammal, Executive Vice-President and Chief Regulatory Operations Officer, CNSC, provided the following highlights, main takeaways and conclusions of the workshop, as well as next steps:

Highlights:

- The workshop was a success, with over one hundred and seventeen participants from fourteen countries. This workshop brought together eminent international experts (regulators, academics, consulting organizations and industry leaders) to share experiences on the topic of MUPSA and safety goals. Feedback received so far indicates that this workshop was a good learning experience for all. The workshop presentations were well presented and received, and they stimulated excellent technical discussions. This workshop provided an excellent forum for sharing new ideas and methods.
- Additionally, it provided the opportunity to share and have discussions concerning:
  - site-based risk metrics,
  - safety goals (IAEA, CNSC, COG, USNRC, United Kingdom),
  - challenges of whole-site PSA methodology,
  - risk aggregation across all units and all hazards.
- The fact that the CNSC is continuing its efforts to encourage international cooperation was applauded.

Main takeaways:

- From this workshop, it is clear that Canada is far ahead on these topics.
- A lot of information was gathered about safety goals development for multi-unit sites from the experience of the USNRC, the Canadian industry and the CNSC.
- Discussions highlighted the potential benefits of a Level 3 PSA to support site safety goals.
- Workshop participants identified the technical challenges of performing a whole-site PSA.

- The topic of MUPSA and safety goals is complex and needs to be reflected upon very carefully. It requires additional deliberations among international PSA practitioners.

Conclusions:

- Although there are some nuances in the safety goals framework, there is common ground for further harmonization through coordination among different organizations.
- The MUPSA implementation is more related to the state-of-the-practice than the state- of-the-art.
- Canada has a strong safety case basis, and the whole-site PSA requirement is part of this effort to protect the health and safety of Canadians.

The next steps are to:

- Develop the workshop report,
- Provide input to the WGRISK project on MUPSA,
- Continue CNSC's effort to develop guidance on MUPSA aggregation methods,
- Continue CNSC's effort to take a leading role internationally in developing whole-site safety goals and in supporting the development of safety design objectives.

Table 10: Plenary Speakers and Topics

Time	Title/Author	Organization	Country
13:15–13:25	**Regulatory Insights for Multi-Unit PSA** Ramzi Jammal Executive Vice-President and Chief Regulatory & Operations Officer	CNSC	Canada
13:25–13:55	**Summaries for each technical sessions by the respective Co-chairs**	-	-
13:55–14:10	**Workshop summary** George Apostolakis (MIT) Karl Fleming (KNFCS)	MIT & KNFCS	United States
14:10–14:20	**Closing address** Yolande Akl	CNSC	Canada

Appendix A: List of Participants

Name	Title and Organization	Country
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Gabriel Balog	Director, Joint Projects and Services, CANDU Owners Group (COG)	Canada
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Appendix B: Acronyms

AERB	Atomic Energy Regulatory Board
ANS	American Nuclear Society
ASME	American Society of Mechanical Engineers
CANDU	Canada Deuterium Uranium
CAPS	CSNI Activity Proposal Sheet
CCF	Common Cause Failure
CDF	Core Damage Frequency
CNSC	Canadian Nuclear Safety Commission
COG	CANDU Owners Group
CSNI	Committee on Safety in Nuclear Institutions
DNGS	Darlington Nuclear Generating Station
DPSE	Darlington Probabilistic Safety Evaluation
EDF	Électricité de France
EME	Emergency Mitigating Equipment
EPRI	Electric Power Research Institute
HRA	Human Reliability Analysis
IAEA	International Atomic Energy Agency
ICDE	International Common Cause Failure Database Exchange
IRSN	Institut de Radioprotection et de Sûreté Nucléaire
ISSC	International Seismic Safety Center
LERF	Large Early Release Frequency
LRF	Large Release Frequency
LWR	Light Water Reactor

MIT	Massachusetts Institute of Technology
MAAP	Modular Accident Analysis Program
MUPSA	Multi-unit Probabilistic Safety Assessment
NEA	Nuclear Energy Agency
NEI	Nuclear Energy Institute
NPP	Nuclear Power Plant
OECD	Organisation for Economic Co-operation and Development
PSA	Probabilistic Safety Assessment
R&D	Research and Development
RIDM	Risk Informed Decision Making
SAMG	Severe Accident Management Guideline
SAP	Safety Assessment Principle
SSC	Structures, Systems and Component
SMR	Small Modular Reactors
SSM	Swedish Radiation Safety Authority
TEPCO	Tokyo Electric Power Company
USNRC	United States Nuclear Regulatory Commission
WGRISK	Working Group of Risk Assessment, under Nuclear Energy Agency