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Status of Site-Level (Including Multi-Unit) Probabilistic Safety Assessment Developments

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COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

Status of Site-Level (Including Multi-Unit) Probabilistic Safety Assessment Developments

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The mission of the NEA is:

– to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes;

– to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management and decommissioning, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

The Committee on the Safety of Nuclear Installations

The Committee on the Safety of Nuclear Installations (CSNI) is responsible for the Nuclear Energy Agency (NEA) programmes and activities that support maintaining and advancing the scientific and technical knowledge base of the safety of nuclear installations.

The Committee constitutes a forum for the exchange of technical information and for collaboration between organisations, which can contribute, from their respective backgrounds in research, development and engineering, to its activities. It has regard to the exchange of information between member countries and safety R&D programmes of various sizes in order to keep all member countries involved in and abreast of developments in technical safety matters.

The Committee reviews the state of knowledge on important topics of nuclear safety science and techniques and of safety assessments, and ensures that operating experience is appropriately accounted for in its activities. It initiates and conducts programmes identified by these reviews and assessments in order to confirm safety, overcome discrepancies, develop improvements and reach consensus on technical issues of common interest. It promotes the co-ordination of work in different member countries that serve to maintain and enhance competence in nuclear safety matters, including the establishment of joint undertakings (e.g. joint research and data projects), and assists in the feedback of the results to participating organisations. The Committee ensures that valuable end-products of the technical reviews and analyses are provided to members in a timely manner, and made publicly available when appropriate, to support broader nuclear safety.

The Committee focuses primarily on the safety aspects of existing power reactors, other nuclear installations and new power reactors; it also considers the safety implications of scientific and technical developments of future reactor technologies and designs. Further, the scope for the Committee includes human and organisational research activities and technical developments that affect nuclear safety.

Foreword

The main objective of the Working Group on Risk Assessment (WGRISK) of the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) Committee on the Safety of Nuclear Installations (CSNI) is to advance the understanding of probabilistic safety assessments (PSA) and enhance PSA utilisation for: improving the safety of nuclear installations; improving the design and operation of nuclear installations; and increasing regulatory effectiveness through risk-informed approaches. Due to its disciplined, integrated and systematic approach, PSA is considered as a necessary complement to traditional deterministic safety analysis.

The mission of WGRISK is accomplished through several activities to exchange PSA-related information among member countries.

Interest in the evaluation of site-level risk, which integrates the various risk contributions from different radiological sources, hazard groups and plant operating states (including risk contributions from concurrent accidents involving multiple co-located radiological sources), has grown since the March 2011 Fukushima Daiichi nuclear power plant accident. In June 2015, the CSNI approved a WGRISK activity to collect information on whether and how member countries are addressing challenges and developments of site-level PSA, and on actual or intended uses and applications of site-level PSA.

The core task group for the WGRISK activity on the status of site-level PSA developments was comprised of representatives from the following countries: Canada, the Czech Republic, France, Germany, the United Kingdom and the United States. The individuals listed in the table below represented their respective organisations and countries as members of the core task group that was responsible for: project planning; administration of project surveys, questionnaires and a workshop; and development of this final report. The NEA wishes to thank these experts, who provided valuable time and considerable knowledge towards this activity.

Name	**Organisation**	**Country**
Yolande Akl (Phase 1 Task Leader) Michael Xu Smain Yalaoui	Canadian Nuclear Safety Commission (CNSC)	Canada
Jaroslav Holy	Ústav Jaderného Výzkumu (UJV) Řež	Czech Republic
Gabriel Georgescu	Institut de Radioprotection et de Sûreté Nucléaire (IRSN)	France
Marina Röwekamp (Phase 2 Task Leader)	Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)	Germany
Joshua Gordon	Office for Nuclear Regulation (ONR)	United Kingdom
Daniel Hudson Nathan Siu	Nuclear Regulatory Commission (NRC)	United States

The NEA administrator responsible for this WGRISK activity was Andrew White.

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Abbreviations and acronyms

CAPS	CSNI Activity Proposal Sheet (NEA)
CCF	Common cause failure
CDF	Core damage frequency
CNRA	Committee on Nuclear Regulatory Activities (NEA)
CNSC	Canadian Nuclear Safety Commission
CSNI	Committee on the Safety of Nuclear Installations (NEA)
EC	European Community
FIRE	Fire Incidents Records Exchange (NEA)
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (Germany)
HRA	Human reliability analysis
IAEA	International Atomic Energy Agency
LERF	Large early release frequency
LRF	Large release frequency
MUPSA	Multi-unit probabilistic safety assessment
NEA	Nuclear Energy Agency
NPP	Nuclear power plant
OECD	Organisation for Economic Co-operation and Development
PRA	Probabilistic risk assessment
PSA	Probabilistic safety assessment
SFP	Spent fuel pool
WGOE	Working Group on Operating Experience (NEA)
WGRISK	Working Group on Risk Assessment (NEA)

Executive summary

Background

The main objective of the Working Group on Risk Assessment (WGRISK) of the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) Committee on the Safety of Nuclear Installations (CSNI) is to advance the understanding of Probabilistic Safety Assessments (PSA) and to enhance PSA utilisation for improving the safety of nuclear installations in the design and operation as well as increasing regulatory effectiveness through risk-informed approaches. Due to its disciplined, integrated and systematic approach, PSA is considered as a necessary complement to traditional deterministic safety analysis.

Two important lessons learnt from the March 2011 Fukushima Daiichi nuclear power plant (NPP) accident were: 1) there can be significant interactions between multiple co-located radiological sources (e.g. reactor units, spent fuel pools or dry fuel storage facilities) on a shared NPP site in response to concurrent or consequential initiators; and 2) the timing of concurrent accident sequences involving multiple site radiological sources can challenge shared structures, systems and components, and resources available for severe accident management and emergency response.

Since this accident, the international nuclear safety community has been exploring whether the traditional single-unit PSA approach is sufficient for assessing the radiological risk associated with accident scenarios for multi-unit sites and if there is a need for an integrated multi-unit PSA (MUPSA) or site-level PSA approach that includes consideration of concurrent accidents involving co-located radiological sources (hereafter named “multi-source accidents”). The international nuclear community has since made significant efforts to enhance the simulation and assessment of such multi-source accident scenarios.

Objectives

In June 2015, the CSNI approved a WGRISK activity on the status of site-level PSA developments, whose objective was to collect information on how member countries are addressing challenges and developments of site-level PSA and actual or intended uses and applications of site-level PSA. .

Task approach

The WGRISK activity on the status of site-level (including multi-unit) PSA developments was completed in two phases. Phase 1 included a preliminary survey and follow-up questionnaires to obtain information about ongoing and future site-level PSA activities in WGRISK member countries. This preliminary survey was used to identify and prioritise three focus areas related to challenges in site-level PSA that were of common interest to member countries: 1) risk aggregation; 2) modelling of multi-source (including multi-unit) interactions or dependencies; and 3) site-based risk metrics and safety goals. Follow-up questionnaires were then developed and administered to member countries to identify and obtain more detailed information about specific technical challenges within each focus area. Findings from these focus area questionnaires then provided the technical basis for the second phase.

Phase 2 consisted primarily of a three-day workshop. The purposes of the workshop were to:

- support the assessment of the current state of site-level PSA methods, models, data and analytical tools;
- support the evaluation of site-level PSA studies;
- share methods, good practices and experiences among member countries on site-level PSA;
- identify new potential topics for further WGRISK activities related to site-level PSA.

Conclusions and recommendations

- Following analysis of the key findings from both phases, the core task group for this WGRISK activity arrived at the following general conclusions with respect to Site-Level PSA developments. The need to assess and manage integrated site risk (and multi-unit risk in particular) has been reinforced as a major topic by the international community. Some countries are developing or implementing statutes (or the equivalent of a statute for that country) or regulations that require site-level PSA, multi-source PSA or MUPSA. Many countries and international organisations have initiated research and development activities, and a number of these activities are intended to be completed within the next few years.
- Integrated site risk assessment and management requires the consideration of challenges in many areas. Areas of particular interest to WGRISK member country participants include: risk aggregation – the aggregation of contributions to risk from various risk contributors (e.g. radiological sources, hazards, different configurations or modes of operation); modelling of multi-source interactions and dependencies; and site-based risk metrics and safety goals.
- There is general agreement on the key challenges. However, member countries and international organisations currently have differing views regarding the best way(s) to address these challenges. Thus, while much progress has been made in developing site-level and multi-unit PSAs since the initiation of the WGRISK activity, the state of practice continues to evolve and there is not yet consensus on approaches for addressing these key challenges.
- As with any complex problem with many potential solutions, various approaches to developing site-level PSA models are possible and are being explored. In particular, member countries are exploring the relative advantages and disadvantages of two fundamental approaches: 1) development of a single, integrated site-level PSA; and 2) logically combining important accident scenarios from "improved" single-source PSA models.
- This WGRISK activity has provided a useful forum for member countries to: exchange information on key activities; identify and prioritise topics of interest; and exchange views on best approaches for handling technical challenges. Based on feedback provided by workshop participants, it is expected that participating

member countries that are currently performing site-level PSAs will benefit from this activity.

Recognising that several site-level PSA activities are underway within member countries and international organisations, the WGRISK should consider a future task aimed at sharing the results and lessons learnt from these activities. In addition, the CSNI and the Committee on Nuclear Regulatory Activities should: consider sponsoring further joint working group or data project activities concerning lessons from operating experience; more generally, continue to support efforts to increase interactions between the WGRISK and relevant NEA working groups and projects; and encourage and facilitate co-operation with the International Atomic Energy Agency on related projects to address the challenges of site-level PSA and MUPSA and associated risk-informed decision-making.

1. Introduction

1.1. Background

The main objective of the Working Group on Risk Assessment (WGRISK) of the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) Committee on the Safety of Nuclear Installations (CSNI) is to advance the probabilistic safety assessment (PSA)[1] understanding and to enhance its utilisation for improving the safety of nuclear installations. Due to its disciplined, integrated and systematic approach, PSA is meanwhile considered as a necessary complement to traditional deterministic safety analysis. To accomplish this mission, the WGRISK carries out a number of activities to exchange PSA-related information between member countries.

The accidents at Three Mile Island and Chernobyl seemed to support a focus on accidents involving individual reactor units that prevailed in the deterministic and probabilistic safety communities. Two important lessons learnt from the March 2011 Fukushima Daiichi nuclear power plant (NPP) accident were (National Research Council, 2014; Miller et al., 2011; INPO, 2011; IAEA, 2015):

- There can be significant interactions between multiple co-located radiological sources (e.g. reactor units, spent fuel pools [SFPs] or dry fuel storage facilities) on a shared NPP site in response to concurrent or consequential initiators.
- The timing of concurrent accident sequences involving multiple site radiological sources may challenge shared systems and resources available for severe accident management and emergency response.

The international PSA community has long recognised the potential for concurrent accidents involving multiple co-located radiological sources at shared nuclear installations (hereafter "multi-source accidents"). However, since the accident at the Fukushima Daiichi NPP, there has been increasing interest among the international nuclear community (see CNSC, 2015) in exploring the extent to which:

- The traditional single-unit PSA approach is sufficient for assessing the total radiological risk to the public from NPP sites comprised of multiple co-located radiological sources; and identifying and characterising significant contributors to total site risk in support of site risk management.
- There is a need for an integrated multi-unit PSA (MUPSA)[2] or site-level PSA approach that considers the potential for concurrent accidents involving multiple co-located radiological sources.

1. In this report, probabilistic risk assessment and probabilistic safety assessment are used synonymously.
2. Strictly speaking, MUPSA can be viewed as applying only to PSA that addresses reactor units. However, to be consistent with usage in previous workshops and publications, this

- The international nuclear community has made significant efforts to enhance the simulation and assessment of such multi-source accidents. A brief summary of notable and relevant efforts is given below.

In January 2014, Canadian nuclear utilities under the CANDU Owners Group Inc. hosted the "International Workshop on Whole-Site Characterization" in Toronto, Canada. This workshop focused on site-level safety goals and holistic approaches to risk assessment.

In May 2014, the Canadian Nuclear Safety Commission (CNSC) published REGDOC-2.4.2 (CNSC, 2014), *Probabilistic Safety Assessment (PSA) for Nuclear Power Plants*, which superseded Regulatory Standard S-294 (same title) to reflect PSA lessons learnt from the Fukushima Daiichi accident, including an explicit requirement to consider the potential for multi-source accidents.

In November 2014, the CNSC hosted the International Workshop on Multi-Unit Probabilistic Safety Assessment in Ottawa, Canada. The objectives of this workshop were to share experience and knowledge related to:

- the development and application of MUPSA;
- the definition and selection of site-level risk metrics for multi-unit NPP sites;
- the development of site-level safety goals and their role in the licensing process;
- the assessment of accident management and offsite consequences for multi-unit NPP sites;
- the development of multi-unit severe accident progression research programmes;
- the challenges in MUPSA and issues requiring further investigation.

Findings from the workshop (CNSC, 2015) served as one of the primary inputs and motivations for the WGRISK activity on the status of site-level PSA developments that is documented in this report.

Since then, several international activities related to one or more aspects of MUPSA or site-level PSA have been undertaken in parallel with this WGRISK activity. Examples of such international activities in which WGRISK members participated or that this WGRISK activity otherwise benefited from include:

- an International Atomic Energy Agency (IAEA) project on development and application of a safety goal framework for nuclear installations;
- an IAEA project to develop a methodology for aggregating risk contributions from various radiological sources, hazard groups and operating states to characterise an overall risk profile;
- an IAEA project to develop and evaluate a methodology and guidelines for performing a Level 1 MUPSA, with limited treatment of Level 2 issues;
- an IAEA project to address considerations in performing integrated risk-informed decision making;

report sometimes uses the term to refer to site-level PSA (i.e. PSA that addresses all potentially important radiological sources on site).

- the Advanced Safety Assessment Methodologies: Extended PSA (ASAMPSA_E) project that led to development of a methodology for modelling multi-unit aspects in case of occurrences of specific external hazards.

1.2. Objectives

In June 2015, the CSNI approved a WGRISK activity on the status of site-level PSA developments.[3] The main objective was to collect information on how challenges and developments of site-level PSA, as well as on the actual and intended uses and applications of site-level PSA, are being addressed by member countries. The task also developed recommendations for follow-on activities.

The task involved the collection of information on:

- how member countries address multi-unit and/or multi-source issues in PSA of NPP sites that contain multiple radioactive sources;
- challenges and developments of site-level PSA;
- actual and intended uses and applications of site-level PSA.

The task was performed in two phases:

- Phase 1 (led by Canada): This phase used surveys and questionnaires to collect information from participating countries regarding their practices on site-level PSA developments, and the specific areas of high interest pertaining to this topic. The results from this phase served as the technical basis for the CSNI site-level PSA workshop performed in Phase 2.
- Phase 2 (led by Germany): This phase consisted of a CSNI/WGRISK workshop on site-level PSA. The workshop expanded on the three focus areas identified during Phase 1: 1) risk aggregation;[4] 2) multi-unit (multi-source) interactions or dependencies; and 3) risk metrics and safety goals.

1.3. Targeted audience

The targeted audience for this report includes a broad spectrum of individuals and entities across the international nuclear community that have an interest in the assessment of risks attributable to potential concurrent accidents involving one or more co-located radiological sources at shared nuclear installations.

1.4. Report structure

This report is comprised of four chapters and supported by three annexes.

- Chapter 2 summarises the approaches used in each of the two phases to achieve the task objectives.
- Chapter 3 summarises the key findings for each of the three focus areas that were identified in Phase 1: 1) risk aggregation; 2) modelling of multi-source

3. The approved CSNI Activity Proposal Sheet for this WGRISK activity is provided in Annex A.
4. The term “risk aggregation” can be defined in many ways. In this report, the term represents the aggregation of contributions to risk from various risk contributors (e.g. radiological sources, hazards, different configurations or modes of operation).

(including multi-unit) interactions or dependencies; and 3) site-based risk metrics and safety goals. In addition, it summarises some of the key technical challenges that were highlighted across both phases.

- Chapter 4 summarises general conclusions and provides recommendations for further activities that follow from these conclusions.
- Annex A [5] provides the Phase 1 survey and responses from participating countries. Other than changing the formatting to be consistent with the rest of the report and correcting obvious typographical errors, the detailed responses that were submitted have been preserved in their entirety. These detailed survey responses are intended to serve as a direct source of information for the benefit of readers.
- Annex B[6] provides the Phase 2 workshop materials: the workshop agenda; the list of participants, including their name, country and organisation; and submitted papers and presentations.

5. Annex A can be found in the document NEA/CSNI/R(2019)16/ADD.

6. Annex B can be found in the document NEA/CSNI/R(2019)16/ADD.

2. Task approach

The Working Group on Risk Assessment (WGRISK) activity on the status of site-level probabilistic safety assessment (PSA) developments was completed in two phases. This chapter summarises the approaches used in each phase to collect information on how member countries are addressing challenges and developments of site-level PSA; and the actual or intended uses and applications of site-level PSA.

2.1. Phase 1: Survey and questionnaires on site-level PSA developments

The Canadian Nuclear Safety Commission served as the lead organisation for Phase 1. This phase included an initial survey and follow-up questionnaires that were administered to obtain information about ongoing and future site-level PSA activities in WGRISK member countries. The initial survey was then used to identify three focus areas related to challenges in site-level PSA that were of common interest to member countries:

- risk aggregation;
- modelling of multi-source (including multi-unit)[7] interactions or dependencies;
- site-based risk metrics and safety goals.

Follow-up questionnaires were then developed for each of these focus areas and sent by email to member countries to identify and obtain more detailed information about specific technical challenges within each focus area. Findings from these focus area questionnaires then provided the technical basis for Phase 2, which is outlined in Section 2.2.

2.1.1. Focus Area 1: Risk aggregation

The objective of this questionnaire was to collect information from participating countries regarding the challenges related to risk aggregation methods at the unit and site level, considering the different degrees of uncertainty and PSA heterogeneity for various hazards. In addition, a questionnaire served for identifying risk aggregation practices for comparison against the safety goals established for each participating member country.

2.2.2. Focus Area 2: Modelling of multi-source interactions or dependencies

The objective of this questionnaire was to collect information from participating countries regarding current practices and considerations, treatments and modelling of multi-source interactions for site-level PSA. A questionnaire was developed and administered to collect information on: the identification and classification of multi-source dependencies; the modelling site-level response for initiating events affecting the whole site; the modelling site-level response to a single-unit (source) event (accident);

7. Hereafter, it is assumed that the term "multi-source" encompasses the term "multi-unit" and that site-level PSA includes MUPSA.

consideration of different plant operating states in the site-level PSA; human reliability analysis modelling for the site-level PSA; interactions in the Level 2 PSA, such as severe accident modelling and simulation for a multi-unit plant; interactions between reactor core and SFP or other significant radiological sources on site; common cause failures (CCFs) modelling across units for the whole-site PSA; and uncertainty analysis for the site-level PSA.

2.2.3. Focus Area 3: Site-based risk metrics and safety goals

The objective of this questionnaire was to collect information from participating countries regarding the definition and regulatory application of probabilistic safety goals, and to investigate the extent to which the currently defined safety goals are applicable to the site level.

Annex A[8] provides the Phase 1 survey materials and responses from participating countries. Other than changing the formatting to be consistent with the rest of the report and correcting obvious typographical errors, the detailed responses that respondents submitted have been preserved in their entirety. These detailed survey responses are intended to serve as a direct source of information for the benefit of readers.

2.2. Phase 2: Workshop on the Status of Site-Level PSA Developments

GRS (Germany) served as the lead organisation for Phase 2 of the task. This phase consisted primarily of a three-day workshop that GRS hosted in Munich, Germany in July 2018. A total of 40 individuals from 13 WGRISK member countries, the Nuclear Energy Agency (NEA), and the International Atomic Energy Agency (IAEA) participated in the workshop. The purposes of the workshop were to:

- support the assessment of the current state of site-level PSA methods, models, data and analytical tools;
- support the evaluation of site-level PSA studies;
- share methods, good practices and experiences among member countries on site-level PSA;
- identify new potential topics for further activities related to site-level PSA.

The workshop was designed to be an extension of Phase 1 that enabled more in-depth exploration and discussion of the focus areas identified in Phase 1. Therefore, the workshop was organised into three sessions that generally aligned with each of the three focus areas (with an expansion of the risk aggregation session to include papers and presentations that more broadly address site-level PSA developments):

- Session 1: Safety goals and risk metrics;
- Session 2: Site-level PSA developments and risk aggregation;
- Session 3: Multi-unit (and multi-source) interactions or dependencies.

The workshop design also benefited from previous WGRISK work relevant to site-level PSA, including past activities on external hazards and round table discussions during

8. Annex A can be found in the document NEA/CSNI/R(2019)16/ADD.

WGRISK annual meetings supporting the latest (post-Fukushima) WGRISK report on the use and development of PSA.

Immediately following the workshop, members of the task group met for a day to formulate key messages and a draft outline for the task report.

Annex B[9] provides the Phase 2 workshop materials: the workshop agenda; the list of participants, including their name, country and organisation; and submitted papers and presentations.

9. Annex B can be found in the document NEA/CSNI/R(2019)16/ADD.

3. Task findings

This chapter summarises the key findings for each of the three focus areas: 1) site-based risk metrics and safety goals; 2) risk aggregation; and 3) modelling of multi-source interactions or dependencies. In addition, it also summarises some of the key technical challenges that were highlighted across both phases. The intent of this chapter is to provide an integrated perspective on the findings from the overall activity, without necessarily distinguishing between Phase 1 and Phase 2, unless there was a clear evolution in thinking from Phase 1 to Phase 2 that is worth highlighting for the reader.

3.1. Site-based risk metrics and safety goals

The objective of the focus area on site-based risk metrics and safety goals was to: collect information from participating member countries regarding the definition and regulatory application of probabilistic safety goals; and investigate the extent to which currently defined safety goals are applicable to the site-level. Key findings for this focus area are summarised below.

3.1.1. Qualitative safety goals

Not all countries have a formal statutory definition for qualitative safety goals. Many countries reference the International Nuclear Safety Advisory Group (INSAG) general nuclear safety objective as a qualitative safety goal, with some countries (e.g. Canada, the Czech Republic, France and India) indicating that INSAG-12 (INSAG, 1999) forms the basis for their safety goals. Per INSAG-12 (INSAG, 1999), the general nuclear safety objective is:

To protect individuals, society and the environment by establishing and maintaining in nuclear power plants an effective defence against radiological hazard.

In some countries, this general nuclear safety objective is also supplemented by qualitative safety goals for individual risk and societal risk.

Some countries have introduced the concept of "practical elimination" in their regulatory framework. This concept is used such that accident conditions leading to large or early releases are either physically impossible or extremely unlikely with high confidence. Two countries (France and Germany) indicated that the application of the practical elimination concept is based on the layers of defence-in-depth. In addition, Canada and the Netherlands stated that practical elimination is only used for new construction plants, while Finland and Hungary apply the concept to both existing and new plants. Finally, Korea and the United States stated that practical elimination is not used within their regulatory frameworks.

3.1.2. Quantitative safety goals or numerical objectives

Some countries (e.g. the Netherlands and the United States) have defined quantitative objectives for so-called surrogate risk metrics related to Level 1 and Level 2 PSA end states that are generally based on quantitative safety goals or numerical objectives/targets related to the risk of radiological health effects, including deterministic effects (e.g. prompt fatalities) and stochastic effects (e.g. latent cancer fatalities). In principle, such surrogate risk metrics are used when a full-scope Level 3 PSA is not available. Examples of surrogate risk metrics include:

- Level 1 PSA: core damage frequency (CDF), fuel damage frequency;
- Level 2 PSA: large early release frequency (LERF), large release frequency (LRF).

The numerical values associated with the safety goals are, in general, consistent with INSAG-12 (INSAG, 1999), where the CDF limits range is 1 E-04 to 1 E-05/year; and the L(E)RF range is 1 E-06 to 1 E-05/year. These numerical values of the safety goals limits are generally used as indicators that are applied for design and operation improvements, and as a target or goal that the level of safety aims to achieve, but not as strict regulatory limits. However, Finland applies a strict regulatory limit of 5 E-07/year for LRF to new reactor designs.

In addition, the scope of numerical objectives/targets varies by country. For example, the United Kingdom applies qualitative and quantitative safety goals for normal plant operation, design-basis fault sequences, individual risks, accident frequencies and societal risks. The quantitative goals are expressed as so-called basic safety levels or basic safety objectives.

3.1.3. Site-based versus unit-based safety goals and risk metrics

Most countries only have qualitative safety goals and numerical objectives/targets for individual reactor units and, for now, do not plan to change their safety goals to address integrated site or multi-unit risk considerations. However, some countries are interested in following developments from countries that are considering changes. For example, public and governmental interest have spurred development of site-based or multi-unit safety goals in Canada and Korea.

The typical Level 1 PSA risk metrics (e.g. CDF) are only applicable to some reactor facilities. For example, CDF may not apply to other reactor facilities (e.g. high-temperature gas-cooled reactors and does not apply to non-reactor radiological sources (e.g. SFPs, dry fuel storage facilities or radioactive waste management facilities). Therefore, CDF is not readily suitable for use in site-level risk characterisation. Some countries (e.g. the Czech Republic, Finland and Germany) are applying alternative risk metrics (e.g. fuel damage frequency) that consider all sources of radioactivity. In addition, there is no international consensus on a quantitative definition of what constitutes a large release for calculating the LRF risk metric for Level 2 PSA. Only a few countries (Canada, Finland, Korea, Sweden, Switzerland and the United Kingdom) have opted to specify the releases in absolute quantities to characterise a large release (e.g. Finland, Korea and Sweden reference any release greater than 100 TBq of Cs-137).

3.1.4. Regulatory application of safety goals

All participants recognised that the form and practice of site-level PSA depends on the intended use and will be affected by their country's safety goals. Participants expressed different member country points of view regarding the comparison of PSA results against numerical objectives and/or targets. For some countries (e.g. the United Kingdom), this practice is discouraged. However, for most countries, such comparisons (with appropriate limitations and caveats) are an integral part of their risk-informed regulatory processes. In most countries, safety goals are not used as strict regulatory limits (see Section 3.1.2 for an exception). Instead, they are used as indicators for risk-informed design and operational improvements, or as targets or goals that countries aim to achieve for the level of NPP safety.

A common trend is that if the damage or release frequencies exceed the safety goal limits or targets (as applicable), appropriate measures are either encouraged or enforced dependent on member country regulatory requirements to make adequate provisions for reducing the risk.

3.2. Risk aggregation

The objective of the focus area on risk aggregation was to collect information from participating member countries regarding: challenges related to risk aggregation methods at the unit and site level, considering the different degrees of uncertainty and PSA heterogeneity for various hazards; and risk aggregation practices for comparison against the safety goals established for each member country.

Consistent with the framework established by the International Atomic Energy Agency (IAEA) risk aggregation project, risk aggregation at the site level encompasses aggregating the contributions to integrated site risk from:

- various radiological sources on the site (e.g. reactor units, SFPs, dry fuel storage facilities);
- various hazard groups, including internal and external hazards (both natural and human-induced);
- various operating states of the site, considering the joint operating states of the radiological sources on the site during a defined operating cycle.

Key findings for the focus area on risk aggregation are summarised below. Key technical challenges pertaining to risk aggregation are described in Section 3.4.

3.2.1. Risk aggregation and PSA limitations

While practices vary across countries, there is increasing interest in assessing and understanding the total aggregated risk from accidents involving all major radiological sources at a nuclear installation. Participants generally agreed that it is important to acknowledge that PSA is one, but not the only, technique for characterising risk and that PSA does not address all potential risk contributors (e.g. deliberate malevolent acts like sabotage or terrorism). Site-level PSA is not necessarily a complete assessment of integrated site risk. This difference provides some of the motivation for a risk-informed approach to decision-making. Participants generally agreed that, in addition to combining quantitative risk contributions, risk aggregation should also consider integrating qualitative risk insights to develop an overall picture of the risk profile for a nuclear installation.

3.2.2. Alternative approaches to risk aggregation

In the context of site-level PSA, whether and how the risks attributed to various radiological sources, hazards and operating states are aggregated will depend on the specific decisions to be informed by the PSA. There are many potential ways to aggregate risk results. Aggregation methods vary from simple addition of the risk contributions from individual radiological sources, hazard groups and plant operating states to development of an integrated PSA model that quantifies the total aggregated risk from all modelled risk contributors. The approach that is used can influence the results and insights that are obtained, including the assessed relative importance of risk contributors. For example, aggregation across an entire site can identify potentially important scenarios overlooked by aggregation across a subset of units on the site. Alternatively, more detailed aggregation schemes (e.g. those that consider timing as well as other source-term characteristics) may be needed. Such schemes might be developed working backward from a site-level PSA that includes offsite radiological consequence analyses (i.e. an integrated site Level 3 PSA).

3.2.3. Accounting for different degrees of realism

There are technical concerns regarding different degrees of realism across the analyses of different risk contributors, particularly with respect to different hazard groups. Alternative solutions to these concerns included presenting disaggregated or both disaggregated and aggregated results; or estimating and adjusting for the degree of bias or systematic error associated with different analyses.

3.2.4. Risk aggregation and operating experience

Participants agreed that leveraging operating experience is important. It is important to ensure that the PSA community attempts to address potentially important issues uncovered by real-world events. For example, multi-site events, sometimes regional in scope, were raised as an issue illustrated by operating experience. Participants noted that the international PSA community could try to be proactive in addressing this issue.

3.3. Modelling of multi-source interactions or dependencies

The objective of the focus area on multi-source interactions or dependencies was to collect information from participating member countries regarding current practices and considerations for treatment and modelling of multi-source dependencies for site-level PSA.

Such multi-source dependencies can include:

- structures, systems and components that are shared between co-located radiological sources (e.g. external power, pumping station, common buildings, shared support systems);
- shared reserve resources between co-located radiological sources (e.g. water, fuel, etc.);
- site mitigation provisions (e.g. an emergency diesel generator for the site that can only be used by one unit at a time);
- connections between co-located radiological sources (e.g. connections that allow for the possibility of using systems from co-located radiological sources);
- potential for inter-unit common cause failure (CCF) events due to use of identical components or identical maintenance in co-located radiological sources on a site);
- correlations in fragilities for structures, systems and components in co-located radiological sources for external hazards (e.g. seismic, flooding, high wind, aircraft crash);
- dependencies arising from physical location (e.g. proximity);

- dependencies arising from human and organisational factors.

In this context, it is important to note countries have already conducted or are in the process of developing multi-unit or whole-site PSAs (e.g. Canada, the Czech Republic, France, Germany, Hungary, Korea, the United States Integrated Site Level 3 PSA). Other countries (Finland, India, Japan, Sweden) are at various stages of developing a multi-unit PSA methodology.

Key findings for the focus area on modelling of multi-source interactions or dependencies are summarised below. Key technical challenges pertaining to the modelling of multi-source interactions or dependencies are described in Section 3.4.

3.1.1. Schemes for classifying inter-source dependencies

There is general agreement regarding the types of dependencies that could be important in site-level PSA. Different organisational schemes are being used to describe and classify inter-source dependencies, but these schemes differ in detail rather than fundamental structure. All the schemes address dependencies observed in multi-unit accidents and incidents, including dependencies due to limited resources (e.g. water, power, staffing) and those associated with cascading effects (e.g. radiation release from a damaged unit inhibiting activities at a co-located, yet undamaged, unit). More generally, it was recognised that operating experience is a valuable source of information for identifying and analysing dependencies.

Participants were specifically asked about whether the existing IAEA scheme for classifying intra-unit dependencies appears to be adequate for classifying inter-source dependencies or whether a new scheme is needed. Most countries clearly indicated that the four types of dependencies identified in IAEA SSG-3 (IAEA, 2010)[10] is adequate, especially at a high level. However, many of these countries also stated that a more refined classification scheme could enhance the identification of potential inter-source dependencies by focusing the analyst's thinking on more specific types of potential inter-unit dependencies. In addition, a few countries indicated that the IAEA classification scheme is insufficient and proposed several new classification schemes to clearly identify the initiating event dependencies, inter-unit phenomenological dependencies, and human or organisational dependencies. Finally, many countries agreed that a list of generic inter-source dependencies and corresponding treatment methods should be made in a systematic approach to facilitate the development of site-level PSA.

3.3.2. Consideration of different hazard groups, initiating events and operating states

The potential impact and relative importance of inter-source dependencies can vary by hazard group, initiating event and operating state for the site (although the distinction between different operating states may matter more for some initiating events than for others). Several countries indicated that the diversity of the sites will pose a challenge in the development of a site-level PSA due to the large number of possible combinations of radiological sources, hazard groups, initiating events and operating states. Most participating member countries are applying a site-level focus on common cause

10. IAEA SSG-3 (IAEA, 2010) defines four types of dependency that have traditionally been used to classify intra-unit dependencies in single-unit PSA: 1) functional dependencies; 2) physical dependencies (spatial dependencies); 3) human interaction dependencies; and 4) component failure dependencies.

initiating events that simultaneously challenge all sources or units on the site (e.g. seismic events; site-wide flooding, loss of shared electrical grid or loss of a shared ultimate heat sink), while some countries are also considering consequential or cascading initiating events (e.g. consequential internal fires, internal floods or loss of offsite power).

3.3.3. Human and organisational factors

Although there was general agreement on the potential importance of organisational factors as a source of dependency between units, there were different, strongly held views on the appropriate treatment of these factors. For example, regarding the observation that different units could be sharing the same procedures, some participants indicated that this sharing should be accommodated using some form of dependency factor, while others argued that an appropriate human reliability analysis (HRA) should account explicitly for the procedures being used, and that the associated human actions are conditionally independent. Participants generally agreed that further work is needed to define what is meant by organisational factors or dependencies in the context of PSA (including site-level PSA) and to determine which aspects should appropriately be modelled within PSA.

More broadly, most countries indicated that the HRA methodology will need to be updated at varying degrees to accommodate multi-unit impacts. In particular, there are some common challenges with regard to considering extreme conditions, prioritisation and limitation of resources, and stress level in site-level HRA. Another identified challenge was that procedures predominantly focus on single-unit actions.

3.3.4. Uncertainty analysis for site-level PSA

Although many countries have not yet considered uncertainty analysis for site-level PSA, most countries do believe that the degree of uncertainty will be increased in a site-level PSA and it is important to address these uncertainties. It was highlighted that a random sampling method to assess parametric uncertainty only represents a small part of the integrated PSA uncertainty (i.e. uncertainty associated with the model and completeness are also important).

The increased uncertainty may be because of human dependencies, inadequate treatment of inter-unit dependencies (component failure dependencies, time-dependent effects and organisational dependencies), or simplified (modelling) assumptions (e.g. a simple aggregation approach to estimate the risk for the whole site, simplified assumptions on unit responses to initiating events).

Several participants indicated that a list of generic sources of uncertainties may help analysts conduct whole-site PSA.

3.4. Key technical challenges

The November 2014 International Workshop on Multi-Unit Probabilistic Safety Assessment resulted in the identification of several technical issues and challenges associated with expanding the scope of PSA to include the contribution to risk from multi-source accident scenarios. These technical issues and challenges were organised into the following technical areas (CNSC, 2015):

- MUPSA infrastructure;
- selection of initiating events;

- accident sequence modelling;
- accident sequence quantification and site-based risk metrics;
- accident progression and source-term characterisation;
- evaluation of radiological consequences;
- site-based safety goals, risk integration and interpretation.

While the international PSA community has made progress in addressing many of the technical issues and challenges that were identified at this workshop, results and insights from this WGRISK activity indicate that most of these technical issues and challenges are still relevant today to some degree. Some of the key technical challenges that were highlighted across both phases of this activity are summarised below.

3.4.1. Site-level PSA infrastructure

Although there are several ongoing site-level PSA projects, there is limited experience and guidance for performing such studies. A notable example includes an ongoing IAEA project to develop and evaluate a methodology and guidelines for performing a Level 1 MUPSA, with limited treatment of Level 2 issues.

There is still a need to revisit and reanalyse international operating experience for lessons to be learnt from significant events and accidents for site-level insights. In addition, this WGRISK activity indicates that the international PSA community is beginning to consider another technical challenge on how to address multi-site risk arising from potential large-scale events that can impact multiple NPP sites within a region. The international PSA community could move forward this issue by examining international operating experience.

3.4.2. Identification of inter-source dependencies

Section 3.3.1 addressed schemes for classifying inter-source dependencies. A thorough search for and characterisation of site-specific inter-source dependencies is essential for performing probabilistic modelling of accident sequences affecting more than one major site radiological source. Systematic approaches are needed to perform such a search for and characterisation of site-specific multi-source dependencies. These approaches may go beyond the traditional approaches used for single-unit PSA, where only intra-unit dependencies are usually identified. Moreover, the results of this task may be difficult to use as the number of potential inter-source dependencies increases with the number of possible combinations of radiological sources, hazard groups, initiating events and operating states to consider. Grouping, screening and iterative approaches may therefore be necessary to obtain representative, yet manageable, information for site-level PSA developments.

3.4.3. Selection of initiating events

Systematic approaches are also needed to identify and characterise the initiating events that can challenge multiple radiological sources on the site. Many of the initiating events considered in single-unit PSAs may be applicable for site-level PSA, but the site context may modify their characterisation (e.g. origin of occurrence, frequency, impact on affected radiological sources, etc.). In addition, the grouping of initiating events for PSA modelling may be different for site-level PSA. Moreover, a systematic approach may lead to the identification of new initiating events that were not yet considered (e.g. transients induced by an accident in a co-located unit).

3.4.4. Accident sequence modelling

The modelling of accident sequences for site-level PSA may be the most important technical challenge. One issue is that there is a lack of deterministic safety analyses of multi-unit accidents to support MUPSA. However, the development of MUPSA may help identify more precisely the need for such supporting analyses. Other issues relate to specific modelling approaches for PSA for multiple units. Some specific issues that should be addressed include:

- Modelling of dynamic accident progression in each radiological source, since it may be affected by the progression of a concurrent accident in a co-located source.
- Modelling of inter-unit CCF and causal dependencies, including functional, human, organisational and spatial dependencies. In this context, the treatment of larger groups of components (large common cause component group size) seems to be a challenge.
- Modelling of additional mitigative measures (e.g. fixed and/or mobile equipment to be used in case of emergencies), which may have been implemented in response to the Fukushima Daiichi accident.
- Modelling of adverse, cascading impacts of an accident involving an individual unit on co-located units, thus creating additional multi-unit accident sequences.
- Modelling of the timing, magnitude and effects of concurrent releases from different units.

Challenges related to data and quantification include:

- Quantification of CCF: There is a need to delineate CCF models and supporting data analysis to address inter-unit and intra-unit CCF events.
- Quantification of human error probabilities in site-level PSA context: There is a need to improve HRA models and analyses to address performance-shaping factors unique to multi-source accidents, including the need to consider how operator actions may be adversely affected by multi-unit interactions or radiological contamination of the site.

Based on the intended uses and selected risk metrics, the resulting PSA models may need to consider new end states involving multi-source accidents and interactions, including the effects of causally related, correlated and uncorrelated (but simultaneously occurring) hazards. Limitations of static PSA modelling approaches may require a re-evaluation using dynamic PSA approaches. In addition, site-level PSA may require the use of mission times beyond the traditional 24 or 72 hours.

Fundamental single-source PSA technical issues also apply within the context of site-level PSA. Although most participants who are performing site-level PSA indicated that they do not intend to address these issues, participants agreed that it is important to acknowledge that some of these fundamental issues may be more important in the context of site-level PSA than in traditional single-source PSA. Some current issues in single-unit PSA modelling that will likely be compounded in site-level PSA include:

- large numbers of accident scenarios;

- impacts of using conservative assumptions to differing degrees for different PSA scope elements (e.g. radiological sources, hazards including hazard combinations or operating states) and at different PSA levels on the ability to develop realistic PSA results;
- treatment of human actions during implementation of severe accident management guidelines and prioritisation of emergency response measures in Level 2 PSA.

3.4.5. Quantification of accident sequence frequencies and interpretation of results

Due to the possible number of combinations of radiological sources and operating states, particularly for sites with more than two reactor units, a site-level PSA model can be large, complex and difficult to quantify. A common theme that emerged in this WGRISK activity is that some simplifications or approximations are being made to manage the scope and complexity of the problem. Some of these simplifications are made to address limitations in available analytical tools. There appear to be opportunities to improve upon the capabilities of available tools to overcome these limitations.

Section 3.2 summarised the key findings for the focus area on risk aggregation. This section highlights key technical challenges pertaining to risk aggregation. Ultimately, whether the risks attributed to various radiological sources, hazards and operating states should be aggregated will depend on the specific decisions to be informed by a site-level PSA. Key risk aggregation challenges include:

- how to account for differing levels of conservatism and uncertainty in the results from different PSA elements that are to be aggregated;
- whether it is appropriate to aggregate results for different radiological sources at the level of fuel damage or whether it is only appropriate to do so at the level of radiological release;
- how to aggregate importance measure results to identify significant risk contributors.

4. Conclusions and recommendations

Building on its analysis of the key findings documented in Chapter 3, the core task group for this Working Group on Risk Assessment (WGRISK) activity developed general conclusions with respect to site-level probabilistic safety assessment (PSA) developments. This chapter summarises these general conclusions and provides recommendations for further WGRISK activities that could follow from them.

4.1. General conclusions

- The WGRISK task on site level PSA, performed in two phases (via a member country survey and a workshop), has resulted in the following conclusions. The need to assess and manage integrated site risk (and multi-unit risk in particular) has been reinforced as a major topic of interest for the international community. Some countries are developing or implementing statutes (or the equivalent of a statute), regulations that require site-level PSA, multi-source PSA or multi-unit probabilistic safety assessment. Many countries and international organisations have initiated research and development activities, and a number of these activities should be completed within the next few years.
- Integrated site risk assessment and management requires the consideration of challenges in many areas. Topics of particular interest to WGRISK member country participants include: risk aggregation – the aggregation of contributions to risk from various risk contributors (e.g. radiological sources, hazards, different configurations or modes of operation); modelling of multi-source interactions and dependencies; and site-based risk metrics and safety goals.
- For the time being, site-level PSA is not advanced enough to perform evaluations of the various approaches for modelling a whole site within PSA. However, the WGRISK site-level PSA task has identified the current challenges to developing approaches.
- There is general agreement as to the nature of key challenges. However, member countries and international organisations currently have differing views regarding the best way(s) to address these challenges. Thus, while much progress has been made in developing site-level and multi-unit PSAs since the initiation of this activity, the state of practice continues to evolve and there is no consensus for addressing the key challenges.
- As with any complex problem with many potential solutions, various approaches to developing site-level PSA models are possible and are being explored. In particular, member countries are exploring the relative advantages and disadvantages of two fundamental approaches to developing a site-level PSA model:

  - Development of a single, integrated site-level PSA. This approach can help provide assurance that important multi-source accident scenarios are not missed. However, due to the large number of potential combinations of radiological sources, hazard groups and plant-operating states, it presents a difficult problem that does not leverage results and insights from available single-source PSA models and could therefore focus resources on issues that may not be important to integrated site risk.
  - Logically combining important accident scenarios from "improved" single-source PSA models. The first step of this approach is to assess, for the risk related to a single radiological source, the impact of the other sources of the site by considering the negative effects (shared systems used by another source, limited resources, increased human error probabilities) and possibly positive effects (mutual backup). This "improved" single-source PSA would thus be able to identify important multi-source effects from the perspective of individual radiological sources. The second step of this approach is to then combine important accident scenarios from the "improved" single-source PSAs to construct a site-level PSA model that can be used to quantify integrated site risk. This approach can help prioritise efforts by focusing attention on accident scenarios that are significant contributors to accident risk involving individual radiological sources, but presents some challenges with respect to ensuring potential multi-source accident scenarios are not missed.
- This WGRISK activity has provided a useful forum for member countries to exchange information on key activities; identify and prioritise topic areas of interest; and exchange views on best approaches for handling technical challenges. Based on feedback provided by workshop participants, it is expected that participating member countries that are currently performing site-level PSAs will benefit from this activity.

4.2. Recommendations to the WGRISK

Recognising that several site-level PSA activities are underway within member countries and international organisations, the WGRISK should consider a future task aimed at sharing the results and lessons learnt from these activities. Such a task should be co-ordinated with other international organisations that are active in this area (notably the International Atomic Energy Agency [IAEA]). In addition, co-ordination with other NEA working groups and ongoing NEA joint projects would also likely provide useful perspectives.

Examples of other NEA working groups to co-ordinate with include:

- the Working Group on Analysis and Management of Accidents;
- the Working Group on External Events;
- the Working Group on Human and Organisational Factors;
- the Working Group on Integrity and Ageing of Components and Structures;
- the Working Group on Operating Experience (WGOE);
- the Working Group on the Safety of Advanced Reactors.

Examples of ongoing NEA projects to co-ordinate with could include:

- the benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Station;
- joint database projects:
  - the International Common-cause failure Data Exchange;
  - the Fire Incidents Records Exchange;
  - the Component Operational Experience, Degradation and Ageing Programme.

4.3. Recommendations to the CSNI and the CNRA

Many of the results and insights of this and related site-level PSA activities have been derived from lessons learnt from the March 2011 Fukushima Daiichi nuclear power plant (NPP) accident as well as from other multi-unit operational incidents. This reinforces the value of operating experience information to PSA.

PSA also provides a useful perspective on operating experience, as indicated by accident precursor analysis programmes in several member countries, as well as by the past WGOE activity on precursors to the Fukushima Daiichi NPP accident (NEA, 2014).

The Committee on the Safety of Nuclear Installations (CSNI) and the Committee on Nuclear Regulatory Activities (CNRA) should: consider sponsoring further joint working group or database project activities concerning lessons from major operational incidents; more generally, continue to support efforts to increase interactions between the WGRISK and the WGOE, and other relevant NEA working groups and projects; and encourage and facilitate co-operation with the IAEA on related projects to address the challenges of site-level PSA and associated risk-informed decision-making.

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