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NUCLEAR ENERGY AGENCY
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Low Power and Shutdown Operations Risk:
Development of Structure for Information Base and Assesment of Modelling Issues

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FOREWORD

As stated in the mandate of CSNI's Working Group on Risk Assessment (WGRisk), the working group supports improved uses of Probabilistic Safety Assessment (PSA) in risk informed regulation and safety management through the analysis of results and the development of perspectives regarding potentially important risk contributors and associated risk-reduction strategies. WGRisk's activities address the PSA methods, tools, and data needed to provide this information.

The joint CSNI/WGRisk and COOPRA report "Improving Low Power and Shutdown PSA Methods and Data to Permit Better Risk Comparison and Trade-off Decision-making" [NEA/CSNI/R(2005)11] concludes that the risk measures between full power and Low Power and Shutdown (LPSD) operations can be comparable, and that the risk insights and profiles can be different. Data and method differences between full power and LPSD PSAs are important in making meaningful risk comparisons and trade-off decisions between these operational conditions.

Since publication of that report, COOPRA project has been discontinued. The current WGRisk task (2007-1) is aimed at expanding the previous work in three specific fields, in order to create an information base and report on the state-of-the-art on LPSD operations risk methods. The following three subtasks were defined. Subtask 1 was to create the structure of an information base (info base) for LPSD operations initiating events (IEs) to support sharing of operational experience in a form suitable for use in PSAs, and to determine the potential need for and feasibility of developing a CSNI data exchange project to support the quantitative analysis of IE frequencies. Subtask 2 was to address insights from recent LPSD investigations and operating experience, and to share information on analysed initiating events and applied methods. Subtask 3 was to collect and share information on how inadvertent human actions resulting in IEs are taken into consideration in LPSD operations PSAs.

This report presents the results of this work and the basis for its main recommendations regarding each of these three subtasks.

In addition to the individuals and organisations listed in the report, whose inputs were invaluable to the task, the Working Group would like to thank in particular E. Lois of US NRC, S. Babst of GRS and S. Hustak of NRI for their coordination of the three subtasks, and A. Amri of the NEA Secretariat for his support throughout this work.

EXECUTIVE SUMMARY

This report addresses the Working Group on Risk Assessment (WGRisk) task (2007-1) on Low Power and Shutdown (LPSD) operations Probabilistic Safety Assessment (PSA). WGRisk is one of the working groups sponsored by the Committee on the Safety of Nuclear Installations (CSNI) and operating under the Organisation for Economic Cooperation and Development (OECD)/Nuclear Energy Agency (NEA). A previous related LPSD international effort included information gathering through (a) the International Cooperative Probabilistic Risk (COOPRA) project, and (b) a previous WGRisk LPSD operations PSA task. COOPRA and WGRisk gathered information from member countries regarding the state-of-the-art of LPSD operations PSA through questionnaires. The questions and responses covered a broad spectrum of LPSD operations PSA topics and identified work for improving risk-informed decisions using PSA techniques. The findings from the COOPRA project and WGRisk task were documented in a common report entitled, *Improving Low Power and Shutdown PSA Methods and Data to Permit Better Risk Comparison and Trade-off Decision Making*" Vols. 1-3, September 2005, NEA/CSNI/R(2005)11. Since publication of that report, COOPRA has been discontinued. The current WGRisk task (2007-1) expands upon the previous work completed, especially into three directions identified as needing further investigation. WGRisk approved initiation of this task in March 2007.

The objectives of the WGRisk LPSD operations PSA task were to expand the previous work in three specific fields, in order to create an information base and report on the state-of-the-art on LPSD operations risk methods. The following three subtasks were defined. Subtask 1 was to create the structure of an information base (info base) for LPSD operations initiating events (IEs) to support sharing of operational experience in a form suitable for use in PSAs, and to determine the potential need for and feasibility of developing a CSNI data exchange project to support the quantitative analysis of IE frequencies. Subtask 2 was to address insights from recent LPSD investigations and operating experience, and to share information on analysed initiating events and applied methods. Subtask 3 was to collect and share information on how inadvertent human actions resulting in IEs are taken into consideration in LPSD operations PSAs.

The approach taken for accomplishing this task was to gather information (through direct interactions and questionnaires) from participating WGRisk member organisations and to document that information in this report. This report documents the findings, summarises the major issues identified, and provides recommendations for addressing any identified issues. The countries that responded to the questionnaire are listed in the following table.

CSNI WGRisk Contributing Members	
Czech Republic	Mexico
France	Slovenia
Finland	Slovakia
Hungary	Spain
Germany	United States
Japan	

Subtask 1 resulted in the development of an info base that was deemed suitable for the qualitative needs of LPSD operations PSAs. However, given the intricacies of LPSD risk evaluations, it would be difficult to use for quantitative PSA tasks and, in particular, for IE frequency estimation. Therefore, the initiation of a project to create an international LPSD database was not recommended. From a qualitative perspective, the proposed infobase represented a necessary step in the development of established practices for LPSD operations PSAs. Given that various ways exist to categorise IEs in LPSD operations PSAs, an agreed upon taxonomy of the various IEs supports harmonisation of IE representation. Through this activity, common definitions of the various parameters used (e.g., reactor level, reactor coolant system vent status) could be established and those parameters needing further interactions could be identified to obtain a common understanding. Therefore, it is recommended that member countries contribute operational events to the info base to create a LPSD event repository in support of LPSD PSAs and LPSD risk applications.

Subtask 2 confirmed the notion that LPSD operations PSAs are widely used in the member countries for the evaluation of the outage risk and for other purposes. Depending on the objectives, authority requirements, and/or available resources, the LPSD operations PSAs differ in extent and in detail. Some countries use flexible models for operating events evaluation and risk monitoring. Differences were identified in the treatment or consideration of various events including: over pressurisation, criticality events, Level 2 PSA, fires, floods, earthquakes, and heavy load drops. It was determined that WGRisk activities could be continued to support the development of a common understanding on the importance of these event sequences to LPSD operations risk as well as establish practices for their treatment. Such activities could lead to improving the understanding of the importance of these initiators and comparing results and insights.

Subtask 3 examined issues related to the modelling of human-induced IEs in LPSD operations PSAs. The followings conclusions were reached.

- Attention should be paid to modelling human-induced IEs in LPSD operations PSAs because they may significantly contribute to risk. The contribution of human-induced events may also be significant when they are grouped with equipment failures, although it is not clearly visible. In either case, human-induced events were a significant part of plant experience during shutdown operations.

- The approaches for separation of human-induced events from equipment failures differed in the various LPSD operations PSAs. Human-induced events were treated as separate IEs to great extent in some PSAs, and in other PSAs they were systematically grouped with equipment failures. The separation of human-induced events was in some cases a result of the IE nature (no credible equipment failure contribution to certain types of IEs). An improper grouping of equipment and human-induced failures may result in inadequate characterisation of risk (either non-conservative or too conservative). The establishment of good practices for separating human-induced events from equipment failures would be useful.

- High-level guidance could be developed for considering and modelling of dependency (e.g., for determination of level of dependency) between a human-induced IE and recovery actions performed by plant staff to restore safety functions upon the occurrence of the IE. The responses to the questionnaire indicated good experience with modelling of such dependency in LPSD operations PSAs.

- Human-induced IEs are typically demand-dependent IEs (also called “per demand” IEs). It is not clear how demand-dependent IEs are represented in the risk profile. The per-demand IEs are time dependent, while the cumulative risk-profile typically used in LPSD PSAs (usually expressed in terms of yearly frequency) is comprised mainly of time-independent or only partially time-dependent IEs. Addressing how to represent the contribution of time-dependent IEs in the risk profile should be pursued to better represent LPSD risk.

Through the information exchange activities, it became apparent that many WGRisk members are pursuing work in different areas and that information exchange through questionnaires has limited ability to convey the advancements achieved. The three fields investigated during this task, although representing an important progress; do not include all the interesting aspects relating to LPSD PSA. As a result, an overall recommendation was developed to hold a workshop on LPSD risk. The objective of the workshop will be to hold a technical exchange on issues identified as needing more work and attention, such as: the use of average versus instantaneous risk, the modelling of human-induced IEs, the treatment of dependencies, and the modelling of interesting LPSD events. Experts performing work in such areas will provide an in-depth discussion of their work and findings, allowing participants to develop a good understanding and appreciation of both the technical issue and how it's being addressed. It also can be used to determine a path forward for using WGRisk as a forum for establishing "good practices" and harmonising LPSD PSA methods and practices.

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1. INTRODUCTION

1.1. Background

This report addresses the Working Group on Risk Assessment (WGRisk) task (2007-1) on Low Power and Shutdown (LPSD) operations Probabilistic Safety Assessment (PSA). WGRisk is one of the working groups sponsored by the Committee on the Safety of Nuclear Installations (CSNI) and operating under the Organisation for Economic Cooperation and Development (OECD)/Nuclear Energy Agency (NEA). WGRisk approved initiation of this task in March 2007. A previous related LPSD international effort included information gathering through (a) the International Cooperative Probabilistic Risk (COOPRA) project, and (b) a previous WGRisk LPSD operations PSA task. COOPRA and WGRisk gathered information from member countries regarding the state-of-the-art of LPSD operations PSA through questionnaires. The questions and responses covered a broad spectrum of LPSD operations PSA topics and identified work for improving risk-informed decisions using PSA techniques. The findings from the COOPRA project and WGRisk task were documented in a common report entitled, *Improving Low Power and Shutdown PSA Methods and Data to Permit Better Risk Comparison and Trade-off Decision Making*" Vols. 1-3, September 2005, NEA/CSNI/R(2005)11. Since publication of that report, COOPRA has been discontinued. The current WGRisk task (2007-1) expands upon the previous work completed, especially into three directions identified as needing further investigation.

1.2 Scope and Objective

The objectives of the WGRisk LPSD operations PSA task were to expand the previous work in three specific fields, in order to create an information base and report on the state-of-the-art on LPSD operations risk methods. Three subtasks were defined. Subtask 1 was to create the structure of an information base (info base) for LPSD operations initiating events (IEs) to support sharing of operational experience in a form suitable for use in PSAs, and to determine the potential need for and feasibility of developing a CSNI data exchange project to support the quantitative analysis of IE frequencies. Subtask 2 was to address insights from recent LPSD investigations and operating experience, and to share information on analysed initiating events and applied methods. Subtask 3 was to collect and share information on how inadvertent human actions resulting in IEs are taken into consideration in LPSD operations PSAs. The U.S. Nuclear Regulatory Commission (NRC) had the overall lead for this task and the lead for Subtask 1; the Gesellschaft für Anlagen-und Reaktorsicherheit (GRS) of Germany had the lead for Subtask 2; and the Nuclear Research Institute (NRI) of the Czech Republic had the lead for Subtask 3.

1.3 Approach

The approach taken for accomplishing this task was to gather information (through direct interactions and questionnaires) from participating WGRisk member organisations and to document that information in this report. The following countries responded to all or parts of the questionnaires for this task:

CSNI WGRisk Contributing Members	
Czech Republic	Mexico
Finland	Slovakia
France	Slovenia
Germany	Spain
Hungary	United States
Japan	

The direct interactions consisted of two meetings. The NRC hosted the first meeting in Rockville, Maryland on October 29-30, 2007. Representatives from OECD, France, Germany, Mexico, and the U.S. attended the meeting. That meeting focused on planning for the project and reviewing the technical proposals prepared by the lead organisations for each of the subtasks. GRS hosted the second meeting in Berlin, Germany, on June 24-26, 2008, which included representatives from the Czech Republic, France, Germany, Japan, Slovenia, and the U.S. The second meeting was a working level meeting in which participants discussed the feedback received from the WGRisk member organisations who responded to the questionnaires. The group evaluated various issues and made decisions on how to compile the information received into a single report representing the views expressed. In addition, the participants discussed what future WGRisk activities should be recommended on the basis of the information collected.

This report summarises the information received from the questionnaires as well as from the meetings' participants. The report documents the findings, summarises the major issues identified, and provides recommendations for addressing any identified issues.

1.4 Continuation of WGRisk LPSD Activities

This report provides a number of recommendations for continuing efforts in the area of LPSD PSA. These recommendations are made recognising that the past COOPRA and WGRisk work, described in Section 1.1, has provided valuable information by summarising the state-of-the-art for LPSD PSA for the time frame reflected in the reports (the Wrist report was published in 2005). These reports indicate that there are many areas in LPSD PSAs in which the technology is still evolving. For example, plant operational states (POSs) definitions vary across PSAs; various definitions and approaches are used in the PSAs from which the information was compiled. Also, sharing operational experience was not part of the COOPRA/CSNI effort. However, operational experience does indicate the intricacies of SD risk; therefore, sharing operational experience information could be valuable for analysts supporting regulatory decision making.

The WGRisk Task 2007-1 collected information on three specific areas: LPSD operational experience, information on analytical issues generated after the COOPRA/CSNI efforts, and the modelling human nduced initiating events with very specific questions beyond those addressed in the COOPRA/CSNI reports. Task2007-1 resulted in a number of recommendations for future WGRisk LPSD activities. The desire for continuation of WGRisk LPSD tasks (extending beyond the completion of Task 2007-1) comes from the recognition that there is substantial work undertaken by countries to improve the understanding, methodology and tools used to evaluate LPSD risk to support the decision. Exchange of information leverages the costs and time associated with addressing LPSD issues. Also, in this task, it is recommended that WGRisk could be used as a forum for establishing "good practices" and harmonising LPSD PSA methodology and practices.

1.5 Organisation of this Report

Chapter 1 provides the background for the WGRisk task on LPSD operations PSA; Chapter 2 summarises the findings from Subtask 1, Information Base; Chapter 3 summarises the findings from Subtask 2, PSA Models and Analytical Issues; Chapter 4 summarises the findings of Subtask 3, Human-Induced Initiating Events; Chapter 5 summarises the conclusions and recommendations and Chapter 6 provides the cited references. Appendices A, B, and C contain the questionnaires developed and the responses received from each country.

2. SUBTASK 1: INFORMATION BASE

2.1 Scope and Objective

The objective of this subtask was to (1) create the structure of an information base (info base) for LPSD operations initiating events (IEs) to support the sharing of operational experience in a form suitable for use in PSAs, and (2) determine the potential need for and feasibility of developing a CSNI data exchange project to support the quantitative analysis of IE frequencies.

A questionnaire addressing these issues was prepared and sent to the member countries to obtain feedback on the proposed structure and on its usefulness for improving LPSD operations risk evaluations. The following countries responded to the questionnaire: the Czech Republic, France, Germany, Japan, Mexico, Slovakia, Slovenia, Spain, and the United States. Appendix A provides the detailed responses from each country. Section 2.2 provides a summary of the responses to the questionnaire and Section 2.3 provides the conclusions for this subtask.

2.2 Summary of the Responses to the Questionnaire

2.2.1 Suitability of the Proposed Structure for Qualitative Analysis

Question: Do you find the info base structure adequate for your needs in developing a better understanding of the risk related to LPSD operations IEs from a qualitative perspective; that is, for understanding the event, its significance, and underlying reasons?

a) If yes, please elaborate on how you may use this info base
b) If not, please provide suggestions for improving it.

<u>Summary of Responses</u>

In general, most countries found the info base useful for developing a qualitative understanding of the risk from LPSD operations. The sharing of operational experience at an international level was cited as one reason. The info base supports understanding of how significant events occur during LPSD operations, as well as the identification and modelling of IEs in a PSA. Most comments received related to the expansion of the information in the info base structure. For example, the structure could indicate if the IE could occur at any time in a POS, in other POSs, and whether it is a LPSD operations' specific IE only. In addition, the need for more contextual information was recommended to allow for a better understanding of the human performance aspects of the IEs.

The Czech Republic noted that the info base could provide a basis for including in the PSA IEs that are not recognised as contributors to risk. Two countries (Slovakia and Spain) recommended the inclusion of containment status. In fact, Slovakia indicated that the info base would not be useful unless containment features were included and noted that a significant difference exists between the western-type PWR containments and the containments of VVER440-type reactors. In VVER440 reactors, if the reactor vessel is open, the containment can be isolated but cannot be closed, which is not the case for western PWRs. This information is needed for the definition of a POS as well as for a level 2 shutdown PSA. As part of its response to a different question, Japan provided specific recommendations for the info base structure. One comment made by Japan was that the info base is biased to human error and does not include component failures to the same extent. These recommendations were taken into consideration, and the info base was revised accordingly.

2.2.2 Suitability of the Proposed Structure for Quantitative Analysis

Question: Do you find the information collected through the proposed info base structure adequate for your needs to develop a quantitative understanding of a LPSD event and its significance?

a) If yes, please elaborate on how you may use this info base.

b) If not, please suggest how it can be improved.

c) Do you find the type and level of information in the structure proposed to be adequate for your needs to develop LPSD event frequencies? If not, please identify what information you would like to have included.

Summary of Responses

Some countries indicated that the info base could be used to develop a quantitative understanding; whereas, other countries did not believe that it could be used for quantification.

Germany noted that the info base could be used for the complete spectrum of IEs for LPSD operations PSAs and, in particular, for the estimation of the frequency of unlikely events that were not observed in German operating experience. Also, Mexico, Slovenia, and Spain indicated that the info base could be useful; assuming that *"Containment Integrity*" type of information was included. Spain recommended the inclusion of information about equipment availability (e.g., number of electrical trains, storage tank level, etc.) and systems status (secondary side).

Japan noted that the "event list" proposed in the info base would be useful for IE selection in a LPSD operations PSA, but that it was not adequate to estimate IE frequencies because of lack of information on event severity (e.g., temperature increase, time to boiling, lost inventory of RCS water, decreased water level). Also, information on reactor vent status and reactor vessel head status is needed for level 2 PSA. Japan provided a discussion from their procedures guide for LPSD operations PSA with regard to whether an event should be included in the frequency estimation. Therefore, to support quantification, the database should include a clear definition of event severity (e.g. temperature increase, time to boiling, lost inventory of reactor coolant, decreased water level) and information on reactor vent status and opening status of reactor vessel head is needed for level 2 PSA.

The Czech Republic noted that the information collected through the proposed structure would not be adequate for frequency estimation. To make this database suitable for quantification, the info base would need to include enough information to (a) understand the event from a risk and safety perspective, (b) decide to what extent a reported event is suitable for inclusion in the PSA of the plant analysed, and (c) determine the additional information related to plant operational characteristics needed for estimating the "denominator" in the IE frequency. The Czech Republic noted that the current info base structure provides most of the information needed for understanding the event. However, the Czech Republic noted that a more detailed event description would be needed to address whether an event was suitable for inclusion in a PSA, and that it provides no information for estimating the denominator in the IE frequency. France noted that the quantitative aspect is much more difficult than the qualitative one (e.g., problems with transferability, completeness, confidentiality), and that discussions are still ongoing on the use of existing OECD data banks (ICDE, OPDE, FIRE, and COMPSIS) for quantitative PSA applications. Slovakia also indicated that the info base would not be useful for frequency estimation.

With respect to last part of this question, Japan noted that a need exists to discuss what information is required for estimation of IE frequencies in LPSD because maintenance practices vary across the countries. In addition, Japan noted that enough of a description of the event should be included in the comment field of the info base (especially for human error) to determine whether it should be considered as an IE in a LPSD operations PSA. Slovakia made similar remarks as the Czech Republic who indicated that because IE frequencies are estimated for each individual POS, information should be included for POS duration as well as the possibility of occurrence of the initiator in a given POS.

Based on this feedback, a database for IE frequency estimation task is not recommended.

2.2.3 Coding of Events

Question: To accomplish the objective of this task of sharing LPSD IE information, would it be possible to

a) Code one or more IEs from your operational experience?
b) Provide comments from your event-coding experience?

Summary of Responses

Several countries coded events and provided insightful comments.

Japan added two events - the criticality event at Shika1 and the loss of RHR event at Genkai1. Germany and Slovenia also added an event. As a result of their coding experience, these countries provided additional comments on the structure of the info base. Japan indicated that the info base was biased toward human error in the sense that it was not asking for equipment- related events at the same level of detail as it was asking for human-related events. Germany indicated that the field related to human performance (“Primary Cause” and “Underlying Factor/Driver”) may not request adequate information so that events occurring in different plants can be coded in one info base and, more so, if the info base was going to be used for calculating IE frequencies.

The other countries indicated that coding events would be an issue of agreement with the utilities and did not code any events. The Czech Republic noted that it had developed broad event-coding experience during development and updating of IE frequencies as part of LPSD operations PSA projects for the two Czech plants, Temelin and Dukovany. As a result, the Czech Republic has developed processes for LPSD event coding. Slovakia provided a breakdown of POSs that could be used to code events.

2.2.4 Definitions of Plant Operating States in the Infobase

Question: With the exception of mid loop, the field for coding in which POS the event occurred is currently undefined. Please suggest how the different POSs should be defined.

Summary of Responses

Several countries provided recommendations for the coding of events into POSs.

Japan recommended that the POSs be grouped by similarity of the plant parameters (determined from thermal hydraulic analysis), the availability of mitigation systems (influenced by maintenance schedule), the IE, the success criteria, and the allowable time. They provided a specific breakdown.

The Czech Republic noted that it would be useful to distinguish the following plant states (or modes):

- Reactor criticality/sub criticality (LPSD operations PSA POSs can begin even with a critical reactor, e.g. below 2 percent of nominal power)

- Temperature below/above RPV brittle fracture temperature
- Performance of reactor coolant system (RCS) pressure sealing/tightness (hydro) test

France noted that the definition of POSs was a very important and difficult question because POSs are plant–specific. Germany provided a breakdown of POSs on the basis of plant parameters and plant status. Mexico noted that the POSs must be defined in terms of the different plant configurations, decay heating, availability of coolant sources, and condition of the vessel (e.g., closed, opened, or connected to the fuel pool). Slovakia noted that, in addition to containment and vessel states, the availability of safety systems (manual or automatic mode), water level in the refuelling cavity (if there is high-water level, the loss of RHR events can be screened out), and electrical power supply should be considered. Slovenia provided the POSs used for the Krško plant. It also noted that POSs from different plants could be gathered and, based on the similarities and/or differences, some generic POSs could be established. Spain proposed POS definitions for both a PWR and BWR plant. The United States developed the proposed structure of the infobase and modified it based on the comments received.

Overall, the countries determined that a need existed to define POSs in terms of general plant parameters, and recommended that POSs be defined in terms of:

- RCS pressure and temperature
- RCS level
- RCS vent status
- Spent fuel status
- Containment status

2.2.5 Feasibility of a Data Exchange Project for Quantitative Analysis

Question: Another objective of this subtask is to determine the potential need for and feasibility of developing a data exchange project to support quantitative analysis of initiating event frequencies.

a) Please express your opinion on both aspects - the need for and the feasibility of. For example, some experts believe that LPSD operations risk may be more important than full-power risk for some POSs and that developing a database appropriate for LPSD operations PSAs will allow the development of a better understanding and modelling of LPSD in PSAs (e.g., the understanding and the modelling of human-induced IEs and associated dependencies).

b) If you would like to see the establishment of such a database, do you think it could be accomplished by taking advantage of other existing event reporting systems such as the International Reporting System (IRS)?

<u>Summary of Responses</u>

All countries agreed that a LPSD data exchange project had merit.

Slovenia stated that LPSD risk was underestimated and had not been investigated enough. Any effort toward developing a better understanding of LPSD risk was viewed as being valuable and welcomed. Data exchange is the most practical way of broadening the knowledge and experience and would thus provide a great gain. Japan noted that such a database could improve the PSA quality by standardising the LPSD operations PSA data needs, establishing IE identification, and screening criteria on the basis of world experience. Mexico noted that it would be helpful to achieve a more realistic understanding of the importance of LPSD operations risk and include in the PSA a more complete scope of IEs (e.g., human-induced IEs). Germany noted that other international databases support the development of frequencies of unlikely events (e.g., frequencies of large leaks at cavity sealing or lining can be estimated on the basis of larger [international] operating experience and that the proposed database is feasible and useful); however, for the understanding and the modelling of human-induced IEs, detailed event descriptions must be given. Slovakia supported the idea and noted that its current LPSD risk is higher than that of full power risk. The United States noted that the establishment an international database would raise awareness of such events.

An IE database was viewed as necessary for a comprehensive understanding of IE frequencies, which are a critical input to all PSAs. Therefore, an IE database is a significant step in deriving these frequencies. For countries with a limited population of plants, derivation of accurate frequencies is difficult because of a lack of data. With an international database, those countries would have a better set of data to develop or at least substantiate their frequencies.

There were also some potential issues raised. The reporting criteria in each country may be different. Also, the amount and level of detail of information offered from each country may vary. If the reporting criteria for LPSD IEs were unified, it was noted that the IRS may adequately cover LPSD events. The reporting criteria should be clear so that it contributes to the quantification of IE frequencies. It was noted that an international exchange needs a rigorous framework including consideration of confidentiality and completeness. With regard to the relationship with other data collection projects, additional assessment was viewed as being needed to avoid overlapping databases and/or inconsistency. Quantitative comparisons can be inappropriate because of differences in operational status, mitigation strategies, and the variability of the refuelling outage schedules; therefore, it would be necessary to establish a minimum POS set. Such a set would help understand the events and associated issues such as the availability of procedures, training, and experience.

Most countries indicated that this task could potentially be accomplished by taking advantage of other existing event-reporting systems such as the IRS. Germany noted that the IRS database contains many safety significant LPSD operations events, and Spain stated that the IRS database contains important information that should be taken into account. The United States noted that in addition to IRS, there are other international reporting systems in place. Examples include the Fire Incidents Records Exchange (FIRE), the International Common-Cause Failure Data (ICDE) Project, the Piping and Failure Exchange (OPDE) Project, and the Exchange of Operating Experience Concerning Computer-based Systems Important to Safety (COMPSIS).

2.2.6 Additional Feedback

Question: If desired, please provide additional feedback on this topic.

Germany noted that the "comments" field of the info base could be renamed to "event description" so that a detailed event description can be entered. Also, Germany noted that it would be helpful to have a measure for the severity of criticality events. Slovakia offered a mathematical model for estimating IE frequency for two different cases - IE frequency from operational experience and for those frequencies derived or extrapolated from corresponding IE frequencies from full power operations. Slovakia also offered a mathematical model for estimating IE frequencies for IEs identified through analysis (such as cold over pressurisation, man-induced LOCA, and boron dilution) and noted that such events would be associated with inadvertent actuations and offered a mathematical formula for estimating such frequency (See Appendix A).

The info base developed as part of this task is attached to this report and could be made available for others to use via the WGRisk website.

2.3 Conclusions

The info base developed was deemed to be suitable for the qualitative needs of LPSD operations PSAs. However, given the intricacies of LPSD risk evaluations, it would be difficult to use for quantitative PSA tasks and, in particular, for IE frequency estimation. Therefore, the initiation of a project to create an international LPSD database was not recommended.

From a qualitative perspective, the proposed info base represented a necessary step in the development of established practices for LPSD operations PSAs. Given that various ways are used to categorise IEs in LPSD operations PSAs, an agreed-upon taxonomy of the various IEs supports harmonisation of IE representation. Through this activity, common definitions of the various parameters used (e.g., reactor level, reactor coolant system vent status) could be established and those parameters needing further interactions could be identified to obtain a common understanding.

A notable example was the definition of POS. During full-power operation, the plant is substantially at steady state and, hence, it can be argued that full power represents just one POS. However, during LPSD operations, the plant goes through many phases and configurations (i.e., POSs). In addition, each outage is different in terms of equipment unavailability, maintenance and testing activities, and their associated timings. Thus, the POS combinations and durations are outage-specific. On the basis of feedback received, it was determined that one can specify those parameters that are universally used to define POSs and use these parameters for POS definition in the information exchange activities. Specifically, a POS can be defined in terms of the following:

- RCS pressure and temperature
- RCS level
- RCS vent status
- Spent fuel status (i.e., before or after refuelling activities have started)
- Containment status

Defining the POS in these terms allows users to translate the POS in their PSA without having to understand all the particular features of the plant/outage or utility's POS definitions in which an event occurred. Adopting this approach may constitute significant progress toward addressing the variability that governs the definition of POSs internationally, which is a fundamental parameter in LPSD operations risk evaluations. Therefore, it is recommended that member countries contribute operational events to the info base to create a LPSD event repository in support of LPSD PSAs and LPSD risk applications.

3. SUBTASK 2: PSA MODELS AND ANALYTICAL ISSUES

3.1 Scope and Objective

The objectives of this subtask were to address insights from recent investigations and operating experience, and to share information on analysed initiating events and applied methods. In a previous NEA/CSNI report, NEA/CSNI/R (2005)11, "Improving Low Power and Shutdown PSA Methods and Data to Permit Better Risk Comparison and Trade-off Decision Making," the scope and objectives of a LPSD operations PSA were addressed.

During the October 29-30, 2007, LPSD planning meeting, participating member countries discussed various analytical issues encountered in conducting a LPSD operations PSA. The countries agreed to collect and share information on the following issues:

- PSA Models for Different Applications
- Average Plant Operating State
- Reactor Coolant System Over pressurisation
- Criticality Events
- Level 2 Analyses and Containment Failure
- Fire, Flooding and Earthquake
- Repair and Knowledge-Based Human Actions
- Heavy Load Drops

A questionnaire addressing these issues was prepared and sent to the member countries. The following countries responded to the questionnaire: the Czech Republic, France, Germany, Japan, Mexico, Slovakia, Slovenia, Spain, and United States. Appendix B provides the detailed responses from each country. Section 3.2 provides a summary of the responses to this questionnaire, and Section 3.3 provides the conclusions for this subtask.

3.2 Summary of the Responses to the Questionnaire

3.2.1 PSA Models for Different Applications

Question: Can you indicate if your LPSD PSA model will be used for different applications (e.g., Tech Spec, event assessment, etc)? If yes:

a) For which applications is your LPSD PSA model used?

b) What are the different specific modelling features foreseen for this purpose?

Depending on the objective and intended use of a PSA, different modelling features may be necessary. For some PSA applications, specific modelling features are needed that may not be needed for other applications. For example, the actual plant configuration has to be modelled for the evaluation of operational events, and for continuous risk monitoring.

Applications of LPSD Operations PSAs

- Czech Republic: The LPSD operations PSA for the Dukovany plant has been used for the following applications: plant modification assessment (safety benefit, acceptability), risk monitoring, risk-informed in-service inspection, event analysis, and Surveillance Testing Interval (STI) extension.

- France: LPSD and full-power operations PSAs are used for similar applications (periodic safety review, probabilistic assessment of events, assessment and improvement of Technical Specifications, Emergency Operating Procedures). There are no particular modelling features for these purposes.

- Germany: The objectives of the LPSD operations PSAs performed by GRS were the application of PSA methods for LPSD operations states to analyse the safety significance, and the development of a basis for a German PSA guideline for LPSD operations PSAs. The licensees are on the way to performing LPSD operations PSAs to support the periodic safety review.

- Japan: Utilities submit the LPSD operations PSA results voluntarily to the regulatory authority for the periodic safety review. The risk information obtained from the LPSD operations PSA is utilised by JNES to investigate the necessity of installation of countermeasures for LPSD operations risk in nuclear power plants. JNES uses LPSD operations PSA in accident sequence precursor studies. Some utilities reduce the risk during maintenance activities, using information obtained from LPSD operations PSA. A procedures guide for LPSD operations PSA is being developed by the Atomic Energy Society of Japan.

- Mexico: The main planned applications of the LPSD operations model of the Laguna Verde nuclear power plant are risk-informed inspections, event assessment, evaluation of modifications to technical specifications, and evaluation of design basis modifications.

- Slovakia: The LPSD operations PSA is used to support risk monitoring and technical specification optimisation.

- Slovenia: Outage Risk Assessment and Management (ORAM) based models are employed for planning, scheduling, and reviewing outages.

- Spain: The objective of the LPSD operations PSAs is to analyse the safety significance of the outage.

- United States: NRC examined the potential risks during LPSD operations and documented those findings in NUREG/CR-6143 and NUREG/CR-6144. Based largely on those studies, NRC has developed Level 1 LPSD operations PSA models and templates. NRC is improving these models for evaluation of events and conditions that occur at licensee facilities during shutdown conditions. Evaluation of events and conditions provide risk information which is used as input into the regulatory decision making process.

Specific Modelling Features for Different Applications

- Czech Republic: The LPSD operations PSA features to be used for applications should be a well-balanced model, with flexibility so that both the average and actual outages and configurations can be analysed.

- Slovenia: ORAM-based model are used which have fault trees and several external event (or “house event”) symbols for interpreting the plant state database.

- Slovakia: Equipment Out of Service (EOOS) configuration risk monitor is used.
- United States: NRC developed (simplified) models for evaluation of events and conditions based on NUREG/CR-6143 and NUREG/CR-6144. Fault tree flag sets and house events are used to set conditions for initiating events in the POSs.

Summary of Responses

LPSD operations PSAs are used for many applications. Examples include:

- Evaluation of outage risk
- Analyses of the safety significance of event sequences during an outage
- Periodic safety review
- Risk-informed decision making
- Evaluation of design modifications
- Optimization of technical specifications and allowed outage times
- Operational event analysis
- Development of PSA guideline for LPSD operations PSAs
- Risk monitoring

The wide use of LPSD operations PSA, including the use for decision making, requires stabilised technologies to obtain high quality and reliable results. In some countries, specific modelling features are used for the evaluation of operational events, or for continuous risk monitoring. Although some guidance documents are available for performing LPSD analysis (e.g., IAEA-TECDOC-1144, NEA/CSNI/R(2005)11), the need for establishing consistent approaches was identified during the meetings held on this topic. For some PSA applications, specific modelling features are needed. Although model flexibility is required to consider different plant configurations, guidance is needed on how to consistently and correctly perform the analysis.

3.2.2 Average Plant Operating State

Questions:

a) Have you developed LPSD structures/models so that both average and actual outages can be facilitated?

b) Does your actual "outage structure" allow the consideration of actual outage equipment unavailability data and POS durations?

LPSD models are typically structured to facilitate calculation of an average outage risk. This means that the models incorporate average outage durations, average length of time in each plant operating state, and average equipment unavailability. However, today regulatory agencies need to perform operational event and condition analysis. The use of average models does not seem to adequately address these needs because no events or conditions occur in average POSs but at highly specific ones.

Development of LPSD structures/models so that both average and actual outages can be facilitated.

- France, Germany, Japan, Mexico, and Spain: The basic LPSD operations PSA structure corresponds to an average outage.

- Some countries developed models that allow the consideration of all plant configurations: risk monitors (Czech Republic, Slovakia), ORAM model (Slovenia).

United States: The American Nuclear Society (ANS) is developing a consensus LPSD operations PRA standard which should help standardise both average-outage and actual-outage LPSD operations PSA models.

Outage structure allowing consideration of actual outage equipment unavailability data and POS durations

- Czech Republic, Slovakia: Risk monitors. Slovenia: ORAM model. These models allow the consideration of all plant configurations.

- France, Spain: If necessary (e.g., for probabilistic analysis of events), the model could be modified to treat actual plant conditions in a specific study.

- Germany: Modifications of the unavailability data and POS durations are, in principle, possible (Risk Spectum Project). Depending on the event sequence, the modifications can be very laborious.

- United States: Current LPSD operations PSA models are geared toward use with actual-outage configurations versus average-outage risk models.

Summary of Responses

Usually LPSD operations PSA models represent an average outage. The modification of a PSA model is in principle possible. Important parameters depending on the POS durations include:

- Frequency of time dependent initiating events

- Human error probabilities (depending on the decay heat, different time spans exist for recovery actions)

- Unavailability data of safety-related systems (depending on testing time and testing frequency, the unavailability of components can change if the POS duration is changing)

Moreover, plant configurations are normally different from outage to outage (i.e., operational systems are available in one outage but not in the next). Also, the number of available trains of safety systems can change from outage to outage. Depending on the plant configuration, the effort to modify the average LPSD operations PSA model can be very high.

For applications that require consideration of variable POS durations or equipment configurations (e.g., for precursor analyses, risk monitoring, risk-informed decision making), special modelling features should be provided in the LPSD operations PSA models which would allow modification to address varying needs with minimal effort.

3.2.3 Reactor Coolant System Overpressurization

Question: Have you taken into account such events in your LPSD PSA? If yes:

a) What events have you considered?

b) What is your definition of core damage for such events?

c) What is the contribution of these events to the overall CDF?

The objective of a level 1 PSA is to determine the frequencies of the different accident sequences leading to core damage. In practice, core damage is replaced by surrogate criteria introduced to simplify the study.

Examples of criteria include prolonged uncovering of fuel assemblies with no possibility of sustained restoration of the water inventory, stresses on the reactor vessel exceeding design basis conditions, injection into the core of a critical volume of insufficiently-borated water, and a maximum cladding temperature.

Another risk during shutdown states is cold over pressurisation of the vessel that can involve a rupture of the primary vessel. Inadvertent injection of safety systems, overfilling, failures of safety valves, or errors during pressure tests can lead to over pressurisation of the reactor coolant system or connected safety related systems. Depending on the RPV design (brittle fracture susceptibility) or the design of relief valves (design for blow down of water), such scenarios can lead to more or less serious consequences.

<u>Considered Events</u>

- Czech Republic: Inadvertent reactor coolant system sub-cooling during reactor coolant system pressure sealing/tightness test. Inadvertent start-up of a high pressure injection pump when temperatures are below the reactor pressure vessel brittle-fracture temperature.
- France: Re-pressurisation of the reactor coolant system when the primary temperature is low has been identified in French PWRs (inappropriate isolation in case of LOCA during cold shutdown).
- Germany: PWR - unlikely scenario, not analysed. BWR - over feeding with residual heat removal system (safety and relief valves are not designed for the blow down of water under full pressure).
- Japan: PWR - Inadvertent operation of high-pressure injection system.
- Mexico: In case of transients and medium/small LOCAs, it may be required to open at least one SRV to decrease pressure in vessel to allow the injection of low pressure systems.
- Slovenia: LOCAs and events that may challenge the integrity of the reactor coolant system or the residual heat removal system and result in an inadvertent relief valve lift were considered. The consequential effects of these events are captured in the small reactor coolant system and residual heat removal LOCA initiators.
- Spain: Such scenarios were considered in the LPSD operations PSA.
- United States: PWR -Initiators considered for pressurised thermal shock for low power (LP) and hot shutdown (HSD) POSs: Reactor turbine trip (LP). Small steam line break (LP/HSD). Loss of main feed water (LP/HSD). Large steam line break (LP/HSD). Small and very small LOCA (LP/HSD) Rupture of steam generator tube (LP/HSD). . Spurious safety injection was also considered as an initiating event for the midloop study. BWR – inadvertent over pressurisation of reactor water cleanup system, spurious actuation of high pressure core spray, LOCA during hydro conditions.

Definition of Core Damage for such Events

- Czech Republic: No specific core damage definition for cold over pressurisation; fuel cladding temperature 1,200°C is generally applied.
- Germany, Spain: Core damage was assumed, when the design pressure of the reactor coolant system was exceeded.
- Mexico: If the core is uncovered over ¾ parts of core length, which is the same as in full-power PSA.
- Slovakia: Reactor vessel rupture leading to core damage.
- Slovenia: No specific definition, core uncovery means core damage.
- United States: Core damage was assumed for ruptures of system piping connected to the RCS boundary and for reactor vessel ruptures for which the core could not be covered.

Contribution of These Events to the Overall CDF

- Czech Republic: Approximately 10 percent of total CDF.
- France: Approximately 5 percent of CDF.
- Slovakia: Less than 1 percent of the overall CDF.
- Germany, Japan, Spain: No influence on the overall CDF.
- Slovakia: No separate quantification.
- United States: NUREG/CR-6144 (PWR) estimated the pressurised thermal shock core damage frequency to be 1E-07/yr.

Summary of Responses

The over pressurisation sequences described in the responses correspond to different situations. There are broadly two categories:

1. Sequences with a rapid pressure increase in the primary circuit when the temperature is low. These sequences could lead to a fragile rupture of the vessel.
2. Sequences with a less rapid pressure increase, which could lead to LOCAs or transients.

The first category could lead to serious consequences. In a French PSA study, the dominant sequence was an inadvertent isolation of the residual heat removal system when the primary circuit was cold, full, and closed. In this situation, the reactor coolant system pressure increases very fast when the temperature remains low, so the limit pressure for fragile vessel failure could be reached if the safety valves are not able to limit this pressure increase. In this case, the assumption is that reaching of the pressure limit leads to vessel rupture. Taking into account this conservative assumption, plant modifications were implemented in France to reduce the corresponding probability.

For the second category, the consequences can be considered to be similar to that for a LOCA or transient.

3.2.4 Criticality Events

Question: Have you taken into account such events in your LPSD PSA? If yes:

a) Explain what events have you considered.
b) Describe supporting analysis for such criticality events.
c) Provide the contribution of these events to the overall CDF.
d) Provide any available reports.

Errors during fuel element or control rod handling can lead locally to (prompt) criticality. Operating experience identified precursors for such criticality events (e.g., Shika 1, Japan, June 1999; Dampierre 4, France, April 2001; Leibstadt, Switzerland, April 2005).

Analysed Events

Six counties have analysed such scenarios:

- Czech Republic: Erroneous withdrawal of control rods during achieving criticality.
- Germany: Erroneous withdrawal of control rods and erroneous removal of control rods.
- Japan: Miswithdrawing of control rods, misalignment of fuel elements, and the inadvertent increase of hydraulic pressure in the hydraulic control unit. Loss of offsite power during boron dilution in start-up of PWR.
- Slovakia: Uncontrolled change in the position of the control rod or control rod group, and the incorrect alignment of the fuel elements in the core or spent fuel pool.
- Spain: For PWR plants, the scenario of error during fuel handling was analysed.
- United States: NUREG/CR-6143 (BWR), NUREG/CR-6144 (PWR) - considered potential for criticality due to fuel misloading.

Supporting Analysis for Criticality Events

In some countries, supporting criticality analyses were performed; in other countries, available safety analysis reports were used to estimate the potential consequences of criticality events.

- Czech Republic: Safety Analysis Report for NPP Dukovany and other analyses for consequence evaluation of fuel element/control rod misposition during refuelling or withdrawal of control rods.
- Germany: Criticality calculations to find configurations that can lead locally to prompt criticality, systematic double stuck rod analysis.
- Japan: Sensitivity analysis was performed to find what analytical conditions lead to fuel damage. The Shika 1 event was not analysed in the PSA due to measures taken which indicate that the probability of such events can be neglected. Analysis was performed for loss of offsite power during boron dilution.
- Slovakia: Supporting TH analysis is performed for the accident scenarios.
- Spain: Analysis came from the FSAR.

Contribution of These Events to the Overall CDF

The contribution of the analysed fuel or control rod handling errors to the overall CDF was fairly low, up to 3 percent of the overall CDF.

- Czech Republic: Up to 2.7 percent of total FDF (including fuel in spent fuel pool) from all POSs (including full power).
- Germany: Approximately 3 percent of the overall CDF for LPSD conditions in the BWR69 plant.
- Japan: CDF of miswithdrawing of control rods is 3 orders lower than the total CDF of LPSD for BWR5. CDF of loss of offsite power during boron dilution is less than 1 percent of the overall CDF for LPSD.
- Slovakia: Less than 1 percent.
- Spain: In one plant (Asco NPP), the contribution is negligible; in the other (Almaraz NPP), the contribution is 2.5 percent of the overall CDF for LPSD PSA.
- United States: NUREG/CR-6144 study (PWR) - the CDF attributable to fuel misloading was estimated to be 1.2E-7/yr.

Summary of Responses

Criticality accidents due to fuel element or control rod handling errors were analysed in six member countries. In some countries, supporting analyses were performed and in other countries, the safety analysis reports were used to estimate the potential consequences of criticality events.

The responses showed a fairly low contribution of the analysed fuel element or control rod handling errors to the overall CDFs, up to 3 percent. These scenarios yield no dominant contribution to the overall CDF. Moreover, the consequences to the environment are not as serious as for core damages due to core uncovery following a LOCA or a loss of RHR, because the core remains covered and most scenarios have consequences only for local bounded core areas.

However, significant precursors for criticality accidents were observed in the operating experience in the member countries (e.g., Shika 1, Japan, June 1999; Dampierre 4, France, April 2001). Therefore, analysis of criticality events should be part of LPSD operations PSA.

Regarding the systematic misloading of fuel elements and the erroneous removal of several control rods, one can a find lack of methodology for the probabilistic evaluation of such scenarios. Establishing a methodology for probabilistic evaluation of such scenarios must be objective of further analyses.

3.2.5 Level 2 Analyses and Containment Failure

Question: Have you performed a Level 2 analysis in your LPSD PSA?) If yes:

a) Explain what methods have you developed/used to quantify containment during LPSD failure probabilities?

b) Provide the resulting "Level 2" probabilities.

c) Provide any available reports.

Level 2 analyses for the shutdown states were performed in the Czech Republic, France, Japan, Slovakia, Slovenia, and the United States.

Methods Used to Quantify Containment Failure Probabilities During LPSD:

- Czech Republic: Full-power level 2 PSA analyses were extended to POS 2 (achieving criticality/sub criticality) and POS 3 (hot shutdown).

- France: Full-power PSA methods were applied with appropriate adaptation of the accident progression event trees.

- Japan: The level-2 PSA procedure for LPSD operations is basically the same as that for power operation. Containment event trees are composed for each plant damage state and used for the identification of potential accident scenarios.

- Slovakia: The pressure capacities of the containment are evaluated using limit state analyses for the various failure modes considered.

- Slovenia: A detailed analysis of containment failure following a LPSD core damage sequence was not done; however, an assessment of the availability of containment and containment protective features coincident with postulated core damage sequences was completed.

- United States: NUREG/CR-6595, "An Approach for Estimating the Frequencies of Various Containment Failure Modes and Bypass Events," Oct. 2004, provides guidance for estimating large early release frequencies under LPSD conditions.

Resulting "Level 2" Probabilities

- Czech Republic: LERF for Plant Operational Modes 2 and 3 is 3.4E-8/yr.

- Japan: Lower than 1/10th of the value of CDF defined as the quantitative safety goal of IAEA/INSAG or the proposed performance index of safety goal by nuclear safety commission in Japan.

- Slovakia: There is a 60-percent probability that the closed containment will successfully maintain its integrity and prevent an uncontrolled fission product release.

- Slovenia: Depending upon the condition of the containment and of the containment fan coolers, the probability of the failure of the containment was estimated for different scenarios.

Summary of Responses

Several countries implemented modelling approaches for estimating large early release frequency (LERF) during LPSD conditions. The modelling approaches relied upon full-power analyses and were adapted for the plant operational states evaluated. Containment event trees (CETs) were developed for both LPSD conditions and for specific modes (e.g., hot shutdown).

LERF PSA studies and guidance have addressed pressurised water reactors, boiling water reactors, and VVER440 reactors. Some of the PSA study results showed a relatively low frequency for the potential of a large early release. However, in some instances, the studies recognised that LERF may be the same as the core damage frequency due to an open containment. LPSD CETs generally considered top-event questions similar to full power PSAs. A common top-event question was the status of the reactor coolant system boundary and the containment. With a direct path to the environment, the potential for a large early release exists. Estimation of the LERF considered the probability of failure to close the containment or failure of containment pressure retaining capability. All uncontrolled releases to the environment may be included in the LERF estimate even though, after shutdown, some source terms considered for full power analyses will have decayed in time and will not be important for the LPSD LERF. The LERF estimate also may take credit for mitigating systems which are not important in full power LERF scenarios, such as containment fan coolers.

Overall, LPSD LERF modelling continues to be a developing area. This survey has shown that modelling and guidance relies to the extent possible on existing full-power PSA analyses and incorporating unique LPSD considerations as necessary. The available references given in the responses are anticipated to be useful to consult.

3.2.6 Fire, Flooding, and Earthquake

Question: What methods you have developed and are using for the treatment of:

a) Internal or external fire during LPSD?
b) Internal or external flood during LPSD?
c) Seismic during LPSD?

LPSD operations PSAs are not treating (internal or external) fire, floods, and seismic events at the same level of detail with those at full power. However, the frequencies of such events, especially fire and flood, may be higher during LPSD operations then at power operation and, therefore, their contribution to risk may be more significant than that at full power. The frequency for fire can be increased for example due to welding or cut off grinding works and fire spreading can be enhanced due to open doors or penetrations.

As operating experience shows, the frequency of internal flooding during LPSD operation can be significantly higher than during full-power operation due to errors in maintenance works.

The questions aimed to the applied or developed methodologies for the probabilistic analysis of fire, floods, and seismic events during LPSD operation.

<u>Fire</u>

In six countries, fire during LPSD operation was analysed.

- Czech Republic: The same methodology as for full power PSA is used in LPSD operations PSA for internal hazards analysis. The shutdown specific features were taken into account (opened doors, higher potential for fire ignition).

- France: Fire was treated for LPSD situations. No specific method was developed, as the full-power PSA methods were applied.

- Germany: Fire in the containment was analysed in the LPSD operations PSA for BWR69 because fire in the containment can occur only during outages. During full-power operation, the containment of this plant type has an inert gas atmosphere to prevent fire. In principle, the same methodology as for full-power fire PSA was applied. A fire specific event tree was modelled, taking into account the outage specific conditions. A specific evaluation of all activities that require fire protection measures was performed.

- Japan: Fire PSA is under development for one POS of a typical plant during LPSD operations.

- Slovakia: Internal fire analysis is performed. The same approach was used as for full-power operation.

- United States: Fire events were considered and analysed in NUREG/CR-6143 and NUREG/CR-6144. NRC is currently developing an improved quantitative fire PRA method to assess a particular plant outage during LPSD operations.

Flooding

- Czech Republic: The same methodology as for full-power PSA is used in LPSD operations PSA for internal hazards analysis. The shutdown specific features were taken into an account.
- Germany: Flooding in the reactor building was analysed in the LPSD operations PSA for BWR69.
- Slovakia: Internal flooding analysis is performed. The same approach was used as for full- power operation. The preventive maintenance activities were taken into consideration.
- United States: Flooding events were considered and analysed in NUREG/CR-6143 and NUREG/CR-6144.

Seismic Events

- Japan: The seismic PSA is under development for some typical plants during LPSD.
- Slovakia: Only a simplified seismic PSA was performed.
- United States: Seismic events were considered and analysed in NUREG/CR-6143 and NUREG/CR-6144.

Contribution of Fire, Flooding, and Earthquake to the Overall CDF

- France: In the IRSN PSA, fire is studied for all reactor states. A first PSA version indicated a non-negligible contribution of LPSD (about 20 percent of the core melt frequency related to LPSD), but in the meantime, several plant improvements were implemented and an updating is in progress for which the results are not yet available. Earthquakes and flooding are not covered presently.
- Germany: Fire in the containment: 3.5E-9/yr (< 0.1 %), internal flooding in the reactor building: 8.1E-8/yr (2 percent).
- Japan: The trial fire PSA was performed only for some important areas in mid-loop operation prior to refuelling for a Japanese PWR. The result of CDF is the same order as that in LPSD PSA for internal events. It is expected to be higher if fire areas and POSs are enlarged for the analysis.
- Slovakia: The contribution of the fire and the flooding to the total core damage frequency during LPSD operation in level 1 PSA is less the than 1 percent for both Mochovce NPP and Bohunice V-2 NPP. The seismic event (earthquake) induced core damage frequency:
  - 2.01E-08/year, it represents 0.23% for Mochovce NPP- 1.12E-06/year, it represents 2.44% for Bohunice V-2 NPP
- United States:
  - NUREG/CR-6143 (BWR) - Internal flooding 2.3E-08 (1%); Seismic 7E-8 (LLNL Hazard Curves) (3%)
  - NUREG/CR-6144 (PWR) - Internal flooding 5.1E006 (18%);Fire 1.8E-5 (63%); Seismic 4E-7 (LLNL Hazard Curves) (1%)

Summary of Responses

No special methods were developed for the evaluation of fire, floods, and seismic events during LPSD operation. The methods developed for full-power operation were applied and/or adapted for LPSD, taking into account the specific shutdown conditions such as higher initiating event frequencies due to maintenance work or enhanced spreading of fire and flood due to open doors or penetrations.

The responses showed that available methods are adequate to analyse fire, floods, and seismic events during LPSD operation. The LPSD specific boundary conditions can be taken into account by adapting the available methodologies.

The frequency of seismic events and the seismic design features depend on the plant site. The responses show no significant contribution of seismic events to the overall CDF.

The contribution of fire, floods, and seismic events to the overall CDF varies. The highest contribution of fire and flooding (63% for fire, 18% for flood) was calculated in the PWR Plant Surry (NUREG/CR-6144). These results show that fire and flooding can be significant contributors to the overall CDF for LPSD operations. Therefore, a detailed analysis of fire and flooding events should be part of a LPSD PSA.

3.2.7 Repair and Knowledge-Based Human Actions

Questions:

a) Are repairs or knowledge-based actions taken into account in your LPSD PSA?

b) If yes, describe the actions.

c) Describe what methodologies were used to quantify these human actions. What was the improvement of the overall result (reduction of CDF) due to taking into account such measures?

Some event sequences in shutdown modes develop slowly. For such event sequences, long time spans for accident control are available. These time spans may exceed 10 or 20 hours and allow measures that are not described in (written) procedures (knowledge-based human actions). Such measures can be the repair of failed components, the reconnection of disconnected systems, or improvising of recovery measures planned after analysis of the situation.

The consideration of repair and knowledge-based human actions can lead to a more realistic evaluation of the risk during LPSD operation and, moreover, to a significant improvement of the overall CDF for LPSD.

Consideration of Repair or Knowledge-Based Human Actions

Knowledge-based human actions (improvising recovery) are taken into account in two countries for selected actions (Czech Republic, Mexico). Repair is considered in four countries (Germany, France, Japan, and Slovenia).

- Czech Republic: Only one pure knowledge-based action was taken into account (termination of safety injection during loss of primary coolant via ECCS tank drainage).

- France: Repair and recovery actions are considered in the LPSD PSA.

- Germany: Repair was taken into account for components for the spent fuel pool cooling (for electrical and I&C equipment).

- Japan: The repair of failed components is considered, but is not considered if it is not included in the procedures.

- Mexico: Restoration is taken into account for components that were on maintenance and surveillance tests. Knowledge-based human actions - actions like systems inter-connections between different NPP units - are included.

- Slovakia: No repair of the components (no component recovery after its failure to operate) is considered in the PSA.

- Slovenia: Operator actions based upon procedures were taken into account. Repair was also taken into account for selected initiating events.

Methods for Quantification of Knowledge-Based Human Actions

- Czech Republic: CREAM/THERP/ASEP depending on the accident scenario.

- Germany: Methodology under development.

- Mexico: Methodology available, data from ASEP.

- United States: ATHEANA methodology, described in NUREG-1624, Rev. 1, "Technical Basis and Implementation Guidelines for A Technique for Human Event Analysis (ATHEANA)," and in NUREG-1880, "ATHEANA User's Guide."

Methods for Quantification of Repair Actions

- Czech Republic: Component repair is credited in one screening criterion applied in PSA for NPP Dukovany. When time to core (fuel) damage for an IE or accident scenario is longer than 24 hrs and components to restore safety functions are repairable, such IE or accident scenario is screened out from PSA.

- France: No specific method was developed. The full-power PSA methods were applied with appropriate choice of PSF.

- Germany: The methodology is based on a human action analysis and defined in the German PSA-Guideline, U.S. data (ASEP, THERP) are used for the reliability of repair actions.

- Japan: The following formula is used for the repair which is the same as that for full power.
  Failure probability to repair = exp $(-T/\tau)$, T: allowable time, τ: mean time to repair.

- Slovenia: The mean time to repair (MTTR) model is applied. For pump, valve, and AC bus repair models, the estimated times required for repair were taken from IEEE Std. 500-1984 "IEEE Guide to the Collection and Presentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability Data for Nuclear Power Generating Stations," from which probabilities of repairs were calculated. The probability of diesel generator recovery was taken from SECY-93-190 "Regulatory Analysis in Accordance with 10CFR50.109: Requirements for Shutdown and Low Power Operations at Nuclear Power Plants."

Summary of Responses

With regard to knowledge-based human actions, methods for quantification of the reliability of knowledge-based human actions are available or under development in a few countries. There is currently no widespread consideration of knowledge-based human actions (improvising recovery) in LPSD operations PSAs. Such measures were taken into account only in two countries for selected actions. For various reasons (no verified methodology, no reliable data, and no international accepted guideline), most countries do not take into account such measures. Nevertheless, a high probability exists for plant personnel to perform knowledge-based human actions when responding to a LPSD abnormal event; therefore, it would be appropriate to consider such events in the PSA. However, established modelling approaches and guidance is needed to correctly reflect plant capabilities for such human actions.

Five countries responded that repair was considered in the LPSD PSAs. Different approaches were used for the consideration of repair. In some PSAs, the "mean time to repair" model was applied. Factors to consider include:

- Transfer of repair data to accident conditions (supply of replacement parts, planning of repair actions)

- Different boundary conditions during the accidents in comparison to normal repair actions (stress, dependency of human actions, accessibility)

- Consideration of parallel repair works

3.2.8 Heavy Load Drops

Questions:

a) What work has been done to identify and quantify such scenarios?

b) What is the contribution of these events to the overall CDF?

c) Are there any reports available describing your methodology and results?

Operating experience shows that heavy load drops during LPSD operations can lead to leaks at the coolant system, the spent fuel pool, or the reactor cavity lining. An example from German operating experience is as follows. An ultrasonic testing device (400kg) was dropped into the gap between the reactor pressure vessel (RPV) and biological shielding. A pipe at the RPV was hit and deformed. A probabilistic fracture mechanical analysis yielded a probability of 0.1 for an unisolable leak above the core, and 0.01 for an unisolable leak underneath the core. Because of this precursor event, pipe breaks at the RPV were taken into account in the German LPSD PSA for the German BWR69 plants.

Analyses of Heavy Load Drops

- Czech Republic: Detailed analysis has been done to identify and quantify scenarios for heavy load drops to the refuelling pool (including drops on RPV) and into the spent fuel pool. The approach in NUREG-0612 was used.

- Germany: Detailed evaluation of the German operating experience was performed to find events that can lead to leaks or loss of safety functions due to heavy load drops. Leaks at the RCS and the spent fuel pool were analysed in the LPSD operations PSA for BWR69 type reactor.

- Japan: Fuel element drop events are screened out from qualitative considerations. The following report, “A Procedures Guide for PSA of Nuclear Power Plants during Shutdown Conditions,” is under development by the Atomic Energy Society of Japan.
- Slovakia: Heavy load drops analysis was performed.
- Spain: Scenarios were screened out due to their very low frequency.
- United States: Not analysed in NUREG/CR-6143 and NUREG/CR-6144. A separate study, NUREG-1774, “Analysis of Crane Operating Experience,” does not provide plant-specific quantification of risk of heavy load drops in various plant locations, but does provide equipment failure rates and probabilities for load drops in general.

Contribution of Heavy Load Drops to the Overall CDF

- Czech Republic: 19% of total Fuel Damage Frequency FDF (including fuel in spent fuel pool) from all POSs (including full power).
- Germany: 0.5% of overall CDF. 80% of the overall frequency for core damage in the spent fuel pool during LPSD conditions.
- Slovakia: Less than 1%.

Summary of Responses

The drop of very heavy loads (e.g., reactor vessel head, spent fuel cask storage, or concrete shielding slabs) was screened out in most PSAs because of the crane design, design of crane tools, and defined crane travel ways. The operating experience in the member countries showed that other load drops (e.g., equipment, tools, or fuel elements) during LPSD operations can lead to leaks at the coolant system, the spent fuel pool, the reactor cavity lining, or the damage of safety-related equipment.

Quantitative analyses of heavy load drops were performed in three countries. Two countries screened out such events by means of qualitative analyses. The results of the probabilistic analyses of heavy load drops showed that these events can yield a significant contribution to the overall CDF, especially given that this initiator directly leads to core damage. The variability among PSAs in the (or lack of) treatment of heavy drop loads leads to inconsistent results as to the importance of this initiator. Therefore, an evaluation of the operating experience as well as the analytical approaches for evaluating the consequences of heavy load drops could be performed as part of a WGRisk activity to develop a common understanding of the importance and a common approach of the treatment of this initiator.

3.3 Conclusions

LPSD operations PSAs are widely used in the member countries for the evaluation of the outage risk and for other purposes. Depending on the objectives, authority requirements, and/or available resources, the LPSD operations PSAs differ in extent and in detail. Some countries use flexible models for operating events evaluation and risk monitoring.

Differences exist in the treatment or consideration of:

- Over pressurisation. Cold over pressurisation can occur due to inadvertent isolation of the residual heat removal system when the primary circuit is cold, full, and closed. In this situation, the RCS pressure increases very fast when the temperature remains low. The pressure limit value for brittle vessel fracture failure could be reached, if the safety valves are not able to limit this pressure increase.

- Criticality Events. Safety significant precursors for criticality accidents were observed in operating experience.

- Level 2 Analyses for LPSD Operation. The risk to the public is caused from the activity release to the environment following core damage. Depending on the POS, the reactor and/or the containment can be open. Therefore, the radioactivity release to the environment could be higher than during full-power operation.

- Fire, Flooding, Earthquake. The responses of the countries that have performed such analyses show that no special methods have to be developed for the evaluation of fire, floods, and seismic events during LPSD operations. The methods developed for full-power operation are adequate, and the specific shutdown conditions can be taken into account.
  Fire and floods can dominate contributions to the overall CDF.

- Heavy Load Drops. Operating experience shows that heavy load drops during LPSD operations can lead to serious impacts. Some responses show significant contribution of the heavy load drops to the overall CDF.

For the above reasons, WGRisk activities could be continued to support the development of a common understanding on the importance of these event sequences to LPSD operations risk as well as establish practices for their treatment. Such activities could lead to improving the understanding of the importance of these initiators and comparing results and insights.

4. SUBTASK 3: HUMAN-INDUCED INITIATING EVENTS

4.1 Scope and Objective

The objective of this subtask was to collect and share information on how inadvertent human actions resulting in IEs are taken into consideration in LPSD operations PSAs. This subtask focused on dependencies between the human-induced IEs and subsequent recovery actions, and on identifying issues that may not be considered in commonly performed HRA and current PSA practices but which may still be important to risk.

A questionnaire was developed for Subtask 3 that focused on the treatment of human-induced IEs in LPSD operations PSA (such human errors are generally referred to as errors of commission). The questionnaire did not include issues such as (1) intentional human actions, (2) human-induced external events, and (3) human errors as a root cause of hardware failures (these are already addressed in component reliability data).

A similar questionnaire developed by COOPRA was previously distributed to some countries. The current questionnaire was expanded to cover additional questions on PSA applications and human error dependency, and to solicit input on unresolved issues. The questionnaire covered the following issues:

- LPSD PSA Main Features
- IE Identification
- Plant Experience
- Systematic Analysis
- Screening Process
- IE Frequency Quantification
- HRA
- Incorporation into PSA
- Treatment in Risk Monitors or Other Applications

Responses were received from the following 11 countries: the Czech Republic, Finland, France, Germany, Hungary, Japan, Mexico, Slovakia, Slovenia, Spain, and the United States. The responses provided information on how human-induced IEs in PSAs have been considered. Some countries provided information gathered from the previous COOPRA questionnaire, while others responded to the current questionnaire. Appendix C provides the detailed responses from each country. Section 4.2 provides a summary of the responses to this questionnaire, and Section 4.3 provides the conclusions for this subtask.

4.2 Summary of the Responses to the Questionnaire

4.2.1 LPSD Operations PSA Main Features

Questions:

a) Present the main objective of your LPSD operations PSA.

b) Present the main PSA applications, in which your LPSD operations PSA are significantly involved.

c) Provide the scope of your LPSD operations PSA as it concerns IEs, and specify the types of IEs currently excluded.

Summary of Responses

In addition to the standard PSA objective, which is an assessment of the overall level of plant safety, the countries indicated that the most frequent objectives were the identification of needed improvement in safety, and the optimisation of plant performance. The usage of LPSD operations PSA varied from country to country. The LPSD operations PSA was used to assess plant outage schedule in several cases. It was also used as a basis for risk monitoring in some countries including the Czech Republic, Slovakia, and Slovenia.

All typical internal events were included in the LPSD operations PSAs; however, in some cases, some events were excluded (e.g., cold over pressurisation in Japan and criticality events in the United States). Internal hazards (e.g., fire) were covered in some of the LPSD operations PSAs, and external events were covered to a lesser extent.

4.2.2 Initiating Event Identification

Questions:

a) Present the definition used to identify IEs for your LPSD operations PSA.

b) Specify whether your LPSD operation PSA includes specific IEs for human-induced events.

c) If not, provide a rationale for your approach and specify whether you see the need to incorporate (or distinguish from equipment failures) specific human-induced IEs into your LPSD operations PSA in the future.

d) If yes, present a brief overview of methods used for identification of human-induced IEs in your LPSD operations PSA. Add example of IEs, for which the particular approach has been decisive to include them into PSA.

Summary of Responses

The IE definitions provided were mostly based on a violation of predefined safety functions, and in some cases on the disturbance of normal operational conditions. Some LPSD PSAs used definitions, which refer to needed actions to bring the plant to a safe and steady-state condition to prevent undesired conditions.

A lot of human-induced IEs were treated in LPSD operations PSAs separately from IEs caused by equipment failures. Their separation was in many cases caused by the nature of the IE, since an equipment failure contribution to some kinds of IEs is not considered. Some countries did not differentiate between human-induced and equipment-induced events.

When human-induced events were not separated from equipment failures in IEs or were not included, the countries indicated that they were considering revising their approach. This would allow for an assessment of the dependency between human errors associated with initiating the event and those associated with recovery actions.

When human-induced events were separated from equipment failures in IEs, a systematic analysis was typically used to identify scenarios for human-induced LOCA (inadvertent RCS drain down). Such analysis was sometimes used to identify the loss of RHR circuit and criticality events. The countries indicated that plant experience was widely considered. In addition, generic lists of IEs and experience from other plants were used in developing the LPSD operations PSAs.

4.2.3 Plant Experience

Questions:

a) Specify whether plant history has been reviewed with specific focus to reveal human-induced IEs to incorporate them in your LPSD operations PSA.

b) If yes, provide a list of human induced events occurred in the analysed unit/plant, which should be considered as IEs by the definition. For each of those events specify, to which IE in your LPSD operations PSA it belongs, or shortly indicate the rationale for its screening from PSA.

Summary of Responses

The countries indicated that plant history had been reviewed with a specific focus on identifying human-induced IEs. Various types of human-induced events occurred in plant history as discussed in the specific responses to the questionnaire.

4.2.4 Systematic Analysis

Questions:

a) Specify whether any kind of systematic analysis has been used to identify human-induced IEs in your LPSD operations PSA.

b) If yes, describe the approach used for systematic analysis to identify scenarios for human-induced IEs in your LPSD operations PSA.

Summary of Responses

When human-induced events were separated from equipment failures in IEs of LPSD operations PSAs, the countries indicated that a systematic analysis was typically used to identify them. The systematic analysis typically consisted of review of outage activities and review of possible RCS delivery/drain down paths (for boron dilution scenarios, human-induced LOCA).

4.2.5 Screening Process

Questions:

a) Specify general assumptions (if any) applied to include human-induced IEs in your LPSD operations PSA, or to eliminate them from the further analysis. Specifically, focus on the cases when:

- Events that could potentially occur were not reported in plant(s) history
- IE selection is performed for POS with no maintenance activity, tests, etc., i.e. there is no context for human error

a) Specify the qualitative criteria applied to eliminate human-induced IEs from further analysis in your LPSD operations PSA (e.g. multiple occurrences of independent failures, 24 hours duration to core damage).

b) Specify the quantitative criteria for screening of human-induced IEs.

<u>*Summary of Responses*</u>

Human-induced IEs were often associated with maintenance activities or some other type of activity/action. Various qualitative criteria were provided in the responses to screen out human-induced events in LPSD operations PSAs. The frequent screening criteria included:

- Core damage is not a consequence
- Multiple occurrences of independent failures
- More than 24 hours duration to core damage

France performs IE screening for LPSD operations PSA based on the severity of consequences. The presence of administrative restrictions and controls to prevent a human-induced event was applied in the Cofrentes LPSD operations PSA as a screening criterion. In Japan, a human-induced event was screened out (considered incredible) if it is not recorded worldwide. A typical quantitative criterion in LPSD operations PSAs described in the responses for the human-induced event frequency applied a screening value between 1E-6/y and 1E-8/y depending on the expected consequence and whether the POS duration was considered in the value. Hungary used a percentage of total LPSD CDF (1%) for screening of boron dilution scenarios.

4.2.6 Initiating Event Frequency Quantification

Questions:

a) Present approaches used for human-induced IEs frequency quantification in your LPSD operations PSA and add a typical IE for each approach.

b) Specify whether and when you consider a human-induced IEs frequency as a time-dependent random event (i.e., the longer is POS, in which the IE is considered, the higher is the frequency) in your LPSD operations PSA. If this is a case, provide a rationale for such approach.

Summary of Responses

The country responses showed that the method for human-induced IE frequency estimation was plant-specific. HRA was typically used for frequency estimation of human-induced LOCA, while direct estimation of IE frequency was often used for excessive drainage (resulting in loss of natural circulation in VVER-440 type plants in the Czech Republic and Slovakia). Generally, estimation from operating experience feedback was applied when relevant information is available, and was preferred especially in France.

Spain and Germany considered their human-induced IEs frequency as demand dependent (i.e., independent of the length of POS), while Slovakia generally considered dependency of such IE frequency on the length of POS. The Czech Republic, France, and Hungary used both approaches depending on the case.

4.2.7 Human Reliability Analysis

Questions:

a) When HRA is used for human-induced IEs frequency quantification in your LPSD operations PSA, describe the HRA quantification method.

b) Indicate the common range of frequencies based solely on HRA for human-induced IEs in your LPSD operations PSA. Use aggregate values for given IE through all applicable POSs.

c) Specify whether dependency between human errors to restore safety functions and human-induced IE is considered in your LPSD operations PSA.

d) If yes, specify how and for which scenarios the dependency mentioned in previous question has been considered in your LPSD operations PSA.

e) If no dependency mentioned in previous questions is assumed in your LPSD operations PSA up to now, specify if you see the need for such dependency analysis and for which cases.

Summary of Responses

The country responses indicated that the typical HRA method used for human-induced IE frequency quantification was THERP. Specific or simple HRA methods were used in some cases. The common frequency range of IEs based on HRA methods started with 1E-3/y (upper limit). The range was very broad in some responses.

When a human-induced event was modelled as a separate IE, the dependency between human errors to restore the safety functions and human-induced IE was considered in most LPSD operations PSAs. The Czech Republic and Slovakia did not consider such dependency.

If dependency between human errors to restore safety functions and human-induced IE was considered, it was usually applied in the model for risk evaluation of mid-loop operation (e.g., for RCS excessive drainage modelling).

The country responses indicated the need to model dependency between human errors to restore safety functions and human-induced IEs depends on the following issues:

- Whether an action leading to an IE and recovery action are performed by the same plant staff
- Whether such dependency would have an impact on the results

4.2.8 Incorporation into PSA

Questions:

a) Specify whether human-induced events are grouped with equipment failures into common IEs. If yes, indicate where such grouping is applied and provide a rationale for this approach.

b) Provide a list of the IEs finally evaluated in your LPSD operations PSA with significant contribution of human errors to IE frequency. Add POSs (with their short description), in which they are applicable and the contribution of human-induced IEs to overall LPSD operations risk.

<u>Summary of Responses</u>

The countries indicated that a lot of human-induced IEs were treated separately from equipment failure IEs. However, their separation was in many cases caused by the IE nature since an equipment failure contribution to some kinds of IEs was not considered. Human-induced events were often grouped with equipment failures into common IEs as well, although the frequency was calculated separately. Japan, Slovenia, and the United States did not differentiate between human-induced and equipment-induced events.

The most frequent human-induced IEs in LPSD operations PSAs were:

- Human-induced LOCA (RCS drain down)
- Reactivity transients (including boron dilution or improper handling of control rods)

Typical human-induced IE in these LPSA operations PSAs also included cold over pressurisation. Less frequent examples were:

- Loss of RHR (drainage or blockage of the circuit)
- Heavy Load Drops
- RCS over draining (low RCS level during regular drainage)
- Spurious PORV Opening

The contribution of human-induced IEs to overall LPSD operations risk was 40-50% for the Czech Republic and Finland. Hungary, Japan, and the United States indicated the possibility of a higher contribution if human-induced events were separated. Germany indicated that the contribution of those events was fairly low (7%).

4.2.9 Treatment in Risk Monitors or Other Applications

Questions:

a) Specify, whether human-induced IEs are part of model used in risk monitor (or for the other applications that require calculation of point-in-time risk), which is based on your LPSD operations PSA.

b) If yes specify, how human-induced IEs frequencies are determined to calculate point-in-time risk in your risk monitor when those events are associated with manipulation/action at NPP. Give the rationale for adopted approach.

c) Specify the time duration, for which the risk from given human-induced to IE is traced in your risk monitor to calculate point-in-time risk, when such event is associated with manipulation/action at NPP.

d) The very short duration of manipulations or even point-in-time nature of manipulations results in very high (or even infinite) point-in-time risk to correspond with cumulative yearly risk as calculated in LPSD operations PSA. Give an opinion whether the current criteria (even not obligatory) for acceptability of point-in-time risk levels in risk monitors are suitable also for human-induced events, whose occurrence is associated with manipulation/action.

Summary of Responses

LPSD operations PSAs were used in the Czech Republic, Slovakia, and Slovenia as a basis for risk monitoring. Human-induced IEs were also part of PSA model used for instantaneous (point-in-time) risk calculation in PSA applications in Finland.

With the exception of the Czech Republic, there were no responses on the approach or how frequencies were determined for monitoring instantaneous (point-in-time) risk from human-induced IEs. The Czech Republic identified a concern about the correct determination of demand dependent IE frequencies used for monitoring instantaneous (point-in-time) risk.

With the exception of the Czech Republic, there were no responses on specification of time duration for monitoring of instantaneous (point-in-time) risk from human-induced IEs. The Czech Republic indicated that the time duration, for which the risk from demand dependent events is traced in risk monitor to calculate point-in-time risk, depends on the case. The Czech Republic identified a concern about the correct determination of the time duration for which the given demand dependent IE would be applicable.

With the exception of the Czech Republic and Japan, there were no responses on the applicability of the current criteria for instantaneous (point-in-time) risk from human-induced IEs. The Czech Republic identified a concern about such applicability.

4.3 Conclusions

NEA/CSNI/R(2005)11 identified human-induced IEs as an important part of a LPSD operations PSA. This subtask examined issues related to modelling of this category of IEs in LPSD operations PSAs. Based on responses to the questionnaire and discussions during task meetings, the followings conclusions were reached.

4.3.1 Contribution of Human-Induced Initiating Events to Risk

Attention should be paid to modelling human-induced IEs in LPSD operations PSAs because they may significantly contribute to risk. The contribution of human-induced events may also be significant when they are grouped with equipment failures, although it is not clearly visible. In either case, human-induced events were a significant part of plant experience during shutdown operations.

The screening of human-induced events based on a predefined scope or simplified screening assumptions may not be appropriate because events excluded are not necessarily a negligible risk contributor. Their low contribution to risk in a similar plant should not be a reason for excluding them from analysis because the low risk could be a result of adopted precaution measures at that particular plant.

4.3.2 Separation of Human-Induced Initiating Events from Equipment Failures

The approaches for separation of human-induced events from equipment failures differed in the various LPSD operations PSAs. Human-induced events were treated as separate IEs to great extent in some PSAs, and in other PSAs they were systematically grouped with equipment failures. The separation of human-induced events was in some cases a result of the IE nature (no credible equipment failure contribution to certain types of IEs).

An improper grouping of equipment and human-induced failures may result in inadequate characterisation of risk (either non-conservative or too conservative). The establishment of good practices for separating human-induced events from equipment failures would be useful. The rationales for such separation could be:

- Different determination and handling of frequency (time dependency of equipment failures vs. demand dependency for most human-induced events), especially for PSA applications.

- Dependency between IE and recovery actions performed by plant staff to restore safety functions upon the occurrence of the IE.

- Understanding of human-induced IEs contribution to risk to determine adequate preventive measures.

The potential risk from human-induced IEs can be usually decreased without expensive or complex measures.

4.3.3 Dependency between Human-Induced Initiating Events and Recovery Actions

High-level guidance could be developed for considering and modelling of dependency (e.g., for determination of level of dependency) between a human-induced IE and recovery actions performed by plant staff to restore safety functions upon the occurrence of the IE. The responses to the questionnaire indicated good experience with modelling of such dependency in LPSD operations PSAs.

Potential important sources for the dependency could be:

- An action leading to an IE and recovery action are performed by the same plant staff.

- Incorrect information from plant measurements/indications, which contributes to confusing plant staff leads to the occurrence of an IE as well as the failure to perform recovery actions.

4.3.4 Treatment of Human-Induced Initiating Events in Risk Monitors and Some PSA Applications

Human-induced IEs are typical of demand-dependent IEs (also called "per demand" IEs). The presentation of a risk profile (normally expressed in term of instantaneous risk, sometimes called point-in-time risk), which includes risk from demand dependent IEs, is not clear. The reason is that the cumulative risk (usually expressed in terms of yearly frequency in LPSD PSAs) from such events is typically time independent or only partially dependent on time. The demand dependency causes problems with specification of the time duration for which the risk from demand dependent IEs should be traced (e.g., in risk monitors). Artificial assignment of the time duration may result in an incorrect presentation of instantaneous risk.

Only a few plants are using LPSD operations PSA as a basis for PSA applications utilising instantaneous risk (e.g., for quantitative risk monitor). Nevertheless, determination of instantaneous risk may become an important issue when LPSD operations PSAs are used more extensively for risk-informed decision making.

The establishment of good practices for determination of instantaneous risk considering demand dependent IEs would be useful. The issues of concern related to those IEs include:

- The calculation and presentation of the instantaneous risk profile.
- The specification of the time duration for which the risk from demand dependent IEs should be traced in a risk monitor.
- The adequacy of an approximation when those events are considered as time dependent (random in time), especially when manipulations that create a context for the IE are frequent and their number is not clear.
- The usage of information from instantaneous risk profile.
- Impact of the change of a number of manipulations and POS duration on the instantaneous risk profile.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Overall Conclusions

A common theme evolved from this information exchange - LPSD risk is not fully understood. LPSD risk is perceived as being low, but in certain POSs, plants are more vulnerable at SD than at full power. Although such states (e.g., hot shutdown) are expected to be well managed and have short duration, operational experience shows instances of expanded duration. Currently, there have not been any good practices established for appropriately reflecting the risk from the various plant shutdown states into the decision making. As a result, the uncertainties associated with LPSD risk assessments are considered to be larger than those for full power.

The use of "average risk" as a risk metric for LPSD may not be as suitable or adequate - at least in certain cases - for LPSD risk evaluations. In some countries, plant shutdown states may have a different system configuration in each outage. As a result, determining an "average" POS configuration for plant shutdown states is difficult. By focusing on the average risk, the significance of short-duration risk spikes may not receive the attention needed. Addressing short-duration risk spikes can help identifying how to lower the risk by, for example, shortening the duration of or decreasing the height of the peak.

The estimation of IE frequency is an area needing attention. If not appropriately addressed, can lead to either over or underestimation of risk. Underestimation can be caused by not reflecting dependencies when various recovery options are considered in the IE frequency estimation; and in the modelling of human actions and support systems in the response part of the IE. Overestimation can be caused by conservative assumptions made regarding recovery capabilities available if the human part is not separately analysed as part of the IE frequency estimation. A topic for future consideration is the establishment of good practices for LPSD risk in general and especially for the modelling and treatment of human-induced IEs in the LPSD PSA. Sharing operational experience can support the IE identification and screening tasks of a PSA. For example, information of rare operational events can guide the PSA analysts to determine if they should include or exclude an IE or how to model it in the PSA.

Full-power operations have benefitted from extensive efforts and experience. A need exists to devote similar efforts to LPSD PSA in order to establish confidence that no hidden vulnerabilities remain which could have been identified and addressed with advanced analytical capability and experience. As a good first effort, the American Nuclear Society (ANS) is developing a standard for LPSD PSAs to be included in the current ASME/ANS PRA standard, RA-Sa-2009, and the International Atomic Energy Agency is finishing a Level 1 PSA standard which also extensively treats LPSD PSA issues. Well-established methods and practices from the international community will improve the quality of LPSD risk evaluations.

Through the information exchange activities, it became apparent that many WGRisk members are pursuing work in different areas and that information exchange through questionnaires has limited ability to convey the advancements achieved. The three specific fields investigated during this task, although representing an important progress; do not include all the interesting aspects relating to LPSD PSA. As a result, an overall recommendation was developed to hold a workshop on LPSD risk. The objective of the workshop would be to hold a technical exchange on issues identified as needing more work and attention, for example, the use of average versus instantaneous risk, the modelling of human-induced IEs, the treatment of dependencies, and the modelling of interesting LPSD events. Experts performing work in such areas could provide an in-depth discussion of their work and findings, allowing participants to develop a good understanding and appreciation of both the technical issue and how it's being addressed.

5.2 Recommendations for Future WGRisk LPSD Activities

The following are recommendations provided for each task and an overall recommendation.

5.2.1 Information Base

Subtask 1, dealt with the development of an info base to support sharing of operational experience. The info base developed as part of this task was deemed to be suitable for LPSD operations PSA needs. However, given the intricacies of LPSD risk evaluations, it would be difficult to use for quantitative PSA tasks and, in particular, for IE frequency estimation. Therefore, the initiation of a project to create an international LPSD database was not recommended.

From a qualitative perspective, the proposed info base represented a necessary step in the development of established practices for LPSD operations PSAs. Given the various ways used to categorise IEs in LPSD operations PSAs, an agreed-upon taxonomy of the various IEs supports harmonisation of IE representation. Through this activity, common definitions of the various parameters used (e.g., reactor level, reactor coolant system vent status) could be established and those parameters needing further interactions could be identified to obtain a common understanding.

A notable example was the definition of POS. During full-power operation, the plant is substantially at steady state and, hence, it can be argued that full power represents just one POS. However, during LPSD operations, the plant goes through many phases and configurations (i.e., POSs). In addition, each outage is different in terms of equipment unavailability, maintenance and testing activities, and their associated timings. Thus, the POS combinations and durations are outage-specific. On the basis of feedback received, it was determined that one can specify those parameters that are universally used to define POSs and use these parameters for POS definition in the information exchange activities. Specifically, a POS can be defined in terms of the following:

- RCS pressure and temperature
- RCS level
- RCS vent status
- Spent fuel status (i.e., before or after refueling activities have started)
- Containment status

Defining the POS in these terms allows users to translate the POS in their PSA without having to understand all the particular features of the plant/outage or utility's POS definitions in which an event occurred. Adopting this approach may constitute significant progress toward addressing the variability that governs the definition of POSs internationally, which is a fundamental parameter in LPSD operations risk evaluations. Although it is not recommended to create a database, it is recommended that member countries contribute operational events to the info base to create a LPSD event repository in support of LPSD PSAs and LPSD risk applications

5.2.2 PSA Models and Analytical issues

Subtask 2, examined specific analytical issues related to the LPSD risk evaluations. From the information gathered, it was concluded that differences exist in the treatment or consideration of:

- <u>Over pressurisation</u>. Cold over pressurisation can occur due to inadvertent isolation of the residual heat removal system when the primary circuit is cold, full, and closed. In this situation, the RCS pressure increases very fast when the temperature remains low. The pressure limit value for brittle vessel fracture failure could be reached, if the safety valves are not able to limit this pressure increase.

- Criticality Events. Safety significant precursors for criticality accidents were observed in operating experience.

- Level 2 Analyses for LPSD Operation. The risk to the public is caused from the radioactivity release to the environment following core damage. Depending on the POS, the reactor and/or the containment can be open. Therefore, the radioactivity release to the environment could be higher than during full-power operation.

- Fire, Flooding, Earthquake. The responses of the countries that have performed such analyses show that no special methods have to be developed for the evaluation of fire, floods, and seismic events during LPSD operations. The methods developed for full-power operation are adequate, and the specific shutdown conditions can be taken into account.
  Fire and floods can dominate contributions to the overall CDF.

- Heavy Load Drops. Operating experience shows that heavy load drops during LPSD operations can lead to serious impacts. Some responses show significant contribution of the heavy load drops to the overall CDF.

It is recommended that WGRisk continue activities in this area. This continued work can support the development of a common understanding on the importance of these event sequences to LPSD operations risk as well as establish practices for their treatment. Such activities could lead to improving the understanding of the importance of these initiators and comparing results and insights.

5.2.3 Human-Induced Initiating Events

Subtask 3 examined issues related to the modelling of human-induced IEs in LPSD operations PSAs. The followings recommendations were reached.

- Attention should be paid to modelling human-induced IEs in LPSD operations PSAs because they may significantly contribute to risk. The contribution of human-induced events may also be significant when they are grouped with equipment failures, although it is not clearly visible. In either case, human-induced events were a significant part of plant experience during shutdown operations.

- The approaches for separation of human-induced events from equipment failures differed in the various LPSD operations PSAs. Human-induced events were treated as separate IEs to great extent in some PSAs, and in other PSAs they were systematically grouped with equipment failures. The separation of human-induced events was in some cases a result of the IE nature (no credible equipment failure contribution to certain types of IEs). An improper grouping of equipment and human-induced failures may result in inadequate characterisation of risk (either non-conservative or too conservative). The establishment of good practices for separating human-induced events from equipment failures would be useful.

- High-level guidance could be developed for considering and modelling of dependency (e.g., for determination of level of dependency) between a human-induced IE and recovery actions performed by plant staff to restore safety functions upon the occurrence of the IE. The responses to the questionnaire indicated good experience with modelling of such dependency in LPSD operations PSAs.

- Human-induced IEs are typically demand-dependent IEs (also called “per demand” IEs). It is not clear how demand-dependent IEs are represented in the risk profile (normally expressed in term of instantaneous risk, sometimes called point-in-time risk), because the cumulative risk from such events is typically time independent or only partially dependent on time. Addressing how to represent the contribution of time independent IEs in the risk profile should be pursued to better represent LPSD risk.

5.2.4 Overall Recommendation

It is recommended a workshop to be held with the objective to have a technical exchange on issues identified as needing more work and attention. Such issues would include: the use of average versus instantaneous risk, the modelling of human-induced IEs, the treatment of dependencies, and the modelling of interesting LPSD events. At the workshop, experts performing work in such areas could provide an in-depth discussion of their work and findings, allowing participants to develop a good understanding and appreciation of both the technical issue and how it is being addressed.

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