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COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

**Informing Severe Accident Management Guidance and Actions for Nuclear Power
Plants through Analytical Simulation**

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COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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

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

Foreword

One of the key lessons learnt from the Fukushima Daiichi nuclear accident is that multiple provisions and countermeasures should be implemented and strengthened in order to increase the capabilities of nuclear power plants (NPPs) to cope with beyond-design-basis accidents (BDBAs¹), including those leading to severe damage to the reactor core and the spent fuel pool. These pre-identified countermeasures and strategies, together with their technical basis and enabling instructions applicable to an NPP, were developed and documented in various forms that are generally referred to as severe accident management guidance (SAMG²). Implementing and enhancing the existing SAMG programme in NPPs, while demonstrating that the SAMG-specified actions are effective under severe accident conditions, is an important post-Fukushima activity.

While it has long been stated that verification and validation of SAMG are crucial activities to assess the success and effectiveness of severe accident management (SAM), there currently appears to be limited guidance on how to perform these activities because of limitations of the existing methods and tools (e.g. full-scope simulators) to represent plausible severe accident conditions. The Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) is working closely with its members and partner countries to address lessons learnt from the Fukushima nuclear accident, including those pertinent to SAM. Special attention is given to identifying best practices worldwide and, on that basis, recommend pragmatic means to assess the feasibility and efficiency of SAM actions.³ As an example of the effort in this area, the NEA Committee on the Safety of Nuclear Installations (CSNI) has endorsed an activity of informing SAMG and actions through analytical simulation, under the Working Group on Analysis and Management of Accidents (WGAMA).

This activity aims firstly to describe the diverse current practices related to SAMG verification and validation. These include expert judgement, simulators, field training, tabletop exercises, emergency drills and exercises and analyses. The second, and larger, part of the activity focuses on a specific technique, namely the use of analytical simulations of the specific SAM including the impacts of operator actions on accident progression. Results of such simulations are used to inform the SAMG developers, users and regulators, and would allow one additional means to assess SAM effectiveness. This approach is seen as providing valuable support for decision making in the technical support centre (TSC) and for increasing confidence in SAM effectiveness.

Emphasis is placed on compiling the current practices related to SAMG verification and validation, particularly pertinent to using analytical simulations as one of the means to increase confidence in SAM actions. The report provides an overview of SAM programme evaluation and its associated activities

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- 1 BDBA is used here in a broad meaning including the design extension condition (DEC).
 - 2 In this report, severe accident management guidance (SAMG) refers to a whole package, which includes all guidelines documents, technical basis documents, enabling instructions, computational aids, etc. Severe accident management guidelines (SAMGs) refer to the guidelines documents such as severe accident guides (SAGs), severe challenge guides (SCGs), etc.
 - 3 In this report, “SAM actions” are used in a broad meaning including all countermeasures for SAM, such as actions that are documented in SAMG as well as in other procedures and guidelines; “SAMG actions” are referred to only the actions as specified in SAMG.

related to SAMG evaluation. Then it focuses on the current toolsets, general methodologies and guidance on use of the analytical simulation to inform SAMG and its specified actions.

The general guidance and information documented in this report should be useful to utility personnel involved in verification and validation of SAMG, as well as to regulatory staff performing evaluation of generic or plant-specific SAMG.

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This report is built on inputs from the participants of this Working Group on Analysis and Management of Accidents (WGAMA) Task Group and extensive consultations and discussions within the Task Group over the past two years.

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List of abbreviations and acronyms

AC	Alternating current
AESJ	Atomic Energy Society (Japan)
AFW	Auxiliary feedwater
AICC	Adiabatic isochoric complete combustion
ALWR	Advanced light water reactor
AOP	Abnormal operating procedure
APR	Advanced power reactor
ART	Analysis of radionuclide transport
ASTEC	Accident source term evaluation code
ATHLET	Analysis of THERmal-hydraulics of LEaks and Transients
ATR	Advanced test reactor
B&W	Babcock & Wilcox
BDBA	Beyond-design-basis accident
BWR	Boiling water reactor
BWROG	Boiling Water Reactor Owner's Group
CA	Calculation aid
CANDU	CANada Deuterium Uranium (reactor)
CD	Core degradation
CE	Combustion engineering
CDF	Core damage frequency
CEA	French Commission for Atomic Energy and Alternative Energies
CET	Core exit thermocouple or temperature
CEOG	Combustion Engineering Owners Group
CFD	Computational fluid dynamics
CHLA	Candidate high-level action
CNRA	Committee on Nuclear Regulatory Activities (NEA)
CNSC	Canadian Nuclear Safety Commission
CNSNS	National Commission of Nuclear Safety and Safeguards (Mexico)

COG	CANDU Owners Group
CSN	Nuclear Safety Council (Spain)
CSNI	Committee on the Safety of Nuclear Installations (NEA)
CSS	Containment spray system
CV	Calandria vessel
CVCS	Chemical and volumetric control system
DBA	Design basis accidents
DC	Direct current
DCH	Direct containment heating
DDT	Deflagration to detonation transition
DEC	Design extension condition
DFC	Diagnostic flow chart (part of SAMG)
DOE	Department of Energy (United States)
DPG	Diagnostic process guideline (part of SAMG)
ECART	ENEL Code for the Analysis of Radionuclide Transport
ECCS	Emergency core cooling system
EDF	Électricité de France
EDG	Emergency diesel generator
EDMG	Extensive damage mitigation guideline
EMEG	Emergency mitigating equipment guideline
ENSREG	European Nuclear Safety Regulators Group
EOP	Emergency operating procedures
EPC	Emergency Procedure Committee (of BWROG)
EPG	Emergency procedure guides
EPR	European pressurised reactor
EPRI	Electric Power Research Institute (United States)
ERC	Emergency response centre
EVR	External vessel retention
EWS	Emergency water supply
FAI	Fauske & Associates
FANC	Federal Agency for Nuclear Control (Belgium)
FLEX	Flexible equipment
FMEA	Failure mode and effect analysis
FROG	FRamatome Owners Group

FSB	Feeder stagnation break
FSG	FLEX Support Guidelines
GE	General Electric
GOTHIC	Generation of Thermal-Hydraulic Information for Containments
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (Germany)
GUI	Graphical user interface
HOP	Human and organisational performance
HPME	High pressure melt ejection
HPSI	High pressure safety injection
HTGR	High temperature gas-cooled reactor
HTS	Heat transport system (in CANDU reactors)
I&C	Instrument and control
IAEA	International Atomic Energy Agency
IAM	Integrated accident management
IDCOR	Industry Degraded Core Rulemaking
IFB	Irradiated fuel bay
INEEL	Idaho National Engineering & Environmental Laboratory (United States)
INL	Idaho National Laboratory (United States)
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (France)
ISAAC	Integrated Severe Accident Analysis Code for the CANDU Plants
ISLOCA	Inter-system loss-of-coolant accident
ISS	Innovative system software
IVR	In-vessel retention
JAEA	Japan Atomic Energy Agency
JAERI	Japan Atomic Energy Research Institute
JNES	Japan Nuclear Energy Safety
KAERI	Korea Atomic Energy Research Institute
KINS	Korea Institute of Nuclear Safety
KIT	Karlsruhe Institute of Technology (Germany)
LAC	Local air cooler
LBLOCA	Large break loss-of-coolant accident
LERF	Large early release frequency
LHF	Lower head failure
LOCA	Loss-of-coolant accident

LPSI	Low pressure safety injection
LWR	Light water reactor
MAAP	Modular Accident Analysis Program (EPRI, United States)
MACCS	MELCOR Accident Consequence Code System
MCCI	Molten core-concrete interaction
MCR	Main control room
MELCOR	NRC's severe accident computer code developed by SNL
NAI	Numerical Applications, Inc.
NEA	Nuclear Energy Agency
NINE	Nuclear and Industrial Engineering (Italy)
NPP	Nuclear power plant
NPSH	Net positive suction head
NRA	Nuclear Regulation Authority (Japan)
NRC	Nuclear Regulatory Commission (United States)
NSSS	Nuclear steam supply system
OECD	Organisation for Economic Co-operation and Development
OSART	Operational safety review team
PARs	Passive autocatalytic recombiners
PIRT	Phenomena identification and ranking table
PHWR	Pressurised heavy water reactor
PORV	Power operated relief valve
PSA	Probabilistic safety assessment
PWR	Pressurised water reactor
PWROG	Pressurised Water Reactor Owners' Group
RBMK	High power channel-type reactor
RCP	Reactor coolant pump
RCS	Reactor coolant system
RHRS	Residual heat removal system
ROP	Reactor oversight process
RPV	Reactor pressure vessel
RWST	Refuelling water storage tank
SAEG	Severe accident exit guideline (part of SAMG)
SAG	Severe accident guide or guideline (part of SAMG)
SAM	Severe accident management

SAMG	Severe accident management guidance (normally refers to the whole package of SAMG established for an NPP)
SAMGs	Severe accident management guidelines (specific guidelines such as SAG and SCG or multiple SAMGs for different NPPs)
SAMP	Severe accident management plan
SBLOCA	Small break loss-of-coolant accident
SBO	Station blackout
SCG	Severe challenge guide or guideline (part of SAMG)
SCST	Severe challenge status tree (part of SAMG)
SFP	Spent fuel pool
SG	Steam generator
SGTR	Steam generator tube rupture
SLB	Steam line break
SNAP	Symbolic Nuclear Analysis Package
SNL	Sandia National Laboratories (United States)
SRS	Safety report series
SSM	Swedish Radiation Safety Authority
TBR	Technical basis report
THALES	Thermal-hydraulic analysis of loss-of-coolant emergency core cooling and severe core damage
TSC	Technical support centre
TSG	Technical support guidelines
UPM	Technical University of Madrid (Spain)
V&V	Verification and validation
VVER	Water-water energetic reactor, or WWER
WENRA	Western European Nuclear Regulator Association
WGAMA	Working Group on Analysis and Management of Accidents (NEA)
WOG	Westinghouse Owners' Group

Executive summary

This report by the Working Group on Analysis and Management of Accidents (WGAMA) summarises the first Nuclear Energy Agency (NEA) project to address the topic of severe accident management guidance (SAMG) verification and validation, with a particular focus on the use of analytical simulations as one of the means to inform SAMG in nuclear power plants. The report describes the current practices aiming at ensuring the correctness, adequacy, usability and efficiency of SAMG, provides an overview of national examples of past and ongoing assessments of severe accident management (SAM) and summarises recommended practices with regard to the use of analytical simulations.

This WGAMA Task Group delivers the following key messages based on a team collaboration and investigation on this topic:

- 1) Symptom-and-knowledge based guidance provides an optimal approach to prevent and mitigate severe accidents. Symptom-based guidance requires adequate knowledge and training to diagnose plant conditions and to identify options that implement viable countermeasures to prevent and mitigate severe accidents. Informing SAMG and actions through analytical simulation is considered as an accumulation of such knowledge.
- 2) A review of the current severe accident computer codes and other complementary computational toolsets indicates that they have been remarkably advanced and extensively tested in recent years. These codes offer capability for modelling key phenomena, physical processes and various progressions of a severe accident with the influences of operators' actions. Using the state-of-the-art computational tools for assessing severe accident progression and consequences with and without operators' actions allows utilisation of the current knowledge and research data in optimisation of SAM actions.
- 3) Analytical support plays an important role in the development, implementation, review, evaluation, maintenance and periodic update of generic or plant-specific SAMG, particularly in terms of understanding the phenomenology of severe accidents and their plant-specific symptoms revealed by plant conditions and available instrumentation.
- 4) Analytical simulation alone may not be sufficient to assess SAM effectiveness. In addition to the insights obtained from the simulations of SAM actions, assessing SAM effectiveness should come from an integral evaluation that takes into account all inputs such as from the review of SAMG documentation, staff qualification and training results, and verification and validation activities such as tabletop exercises, plant walk-throughs, and drills and exercises, etc.
- 5) Analytical methods (such as simulations using computational toolsets, e.g. severe accident analysis computer codes) form part of the SAMG basis, but expert opinion and understanding of plant systems and capabilities are equally viewed as important in the development and evaluation of SAMG.
- 6) Informing SAMG and actions through analytical simulation is a practical and commendable practice, which supplies the personnel who assess the SAMG with detailed information required to understand and characterise the SAM strategies and the associated implementing actions in

such a way that the feasibility and efficiency of those actions under foreseen severe accident conditions can be assessed.

- 7) The purposes of assessment of a SAMG-specified action are not only to assess whether the action will likely achieve its intended function, but also to quantify the environmental conditions under which the action is being implemented, assess its positive and negative impacts, and provide insights and rationales that are useful for the technical support centre (TSC) experts to evaluate and then to select or reject the action or make a rule for its correct timing and necessary prerequisites for the success in a real event, or for the SAMG developers and implementers to reconsider or refine the action in the next update.
- 8) Treatment of simulation uncertainty still remains a serious challenge for assessing SAM actions using analytical tools. Such an assessment should be performed using the best-estimate approach. The associated uncertainties should be recognised, assessed (e.g. by sensitivity analyses, comparison with experiments and calculations using different severe accident analysis codes, or integrated statistical uncertainty analyses), and if necessary, quantified and taken into account in the action assessment. Expert judgement plays an important role in the interpretation of simulation results and overall evaluation of SAM actions in foreseen severe accident conditions of the affected unit.

Establishing and maintaining multiple layers of defence against any internal/external events that could lead to severe damage to the reactor core and the spent fuel pool in a nuclear power plant (NPP) is an important measure to reduce radiological risks to the public and the environment, as accentuated by the Fukushima Daiichi accident in 2011. Moreover, the global nuclear community requests reliable accident management capabilities to deal with extreme internal/external hazards at NPPs.

NPPs meet rigorous nuclear safety rules and standards and incorporate defence-in-depth. Multiple layers of defence come from various on-site and off-site components including infrastructure, equipment, procedural, human and organisational resources. Integrated accident management (IAM) provides an integrated approach to utilise all available resources. IAM is considered a commendable approach to accident management by the Committee on Nuclear Regulatory Activities (CNRA). The CNRA made this recommendation after addressing lessons learnt from the Fukushima Daiichi nuclear accident. According to the recent NEA report, “Accident Management Insights after the Fukushima Daiichi NPP Accident” [1], IAM is defined as:

“...the expansion of existing accident management approaches into a comprehensive approach, combining current good practices and new findings coming from post-Fukushima studies that incorporates all arrangements needed to manage as efficiently as possible any accident affecting the NPP with potential release of radioactive material.”

Accident management procedures and guidelines have been developed to help operators prevent or mitigate the impacts of accidents at NPPs. Accident management consists of two procedure-based activities that are focused on prevention and mitigation. With regard to core damage prevention, emergency operating procedures (EOPs) are symptom-based rules providing the defence-in-depth to event-based procedures (or any other equivalent procedures such as abnormal incident manuals, abnormal operating procedures, etc.), all of which are used to deal with design basis accidents (DBAs) and accidents beyond the design basis with the aim that they do not become severe accidents. Principles and guidance for the development, implementation, verification, validation and documentation of these procedures have been well established such as in International Atomic Energy Agency (IAEA) Safety Report Series No. 48 [2] and United States Nuclear Regulatory Commission (NRC) NUREG-0899 [3]. More importantly, EOPs can be and are continuously exercised by plant operators, either through use of simulators, drills and exercises, or through actual events.

To supplement and enhance EOPs, SAM was first introduced in the 1990s with the creation of severe accident management guidelines (SAMGs) following recognition that post-Three Mile Island EOPs did not adequately address severe core damage conditions. With regard to mitigation of core damage, SAM utilises all the available on-site and off-site resources in such a way that, should a severe accident occur, the NPP can be returned to a condition in which the nuclear chain reaction is terminated, continued fuel cooling is ensured and radioactive materials are confined.

The industry's focus is on accident prevention with most of the resources (e.g. for training) dedicated to this aspect. SAM guidelines such as SAMG are integrated with EOPs and are part of the training programmes. The integration ensures smooth transition from EOPs to SAMG by clearly and consistently defining the entry and exit conditions among the procedures and the guidelines. It appears that the operators of nuclear facilities have drawn a distinction between mandatory following of EOPs and the non-mandatory guidance in SAMG. Due to the higher uncertainties associated with the severe accident progression, SAMG guidance is preferred to allow the responders flexibility when it is used, and practices used to assure the effectiveness of SAM measures as specified in SAMG have not been developed and implemented to the same extent as the EOPs.

Nevertheless, NPP operators are expected to demonstrate that the SAMG-specified actions can be executed under severe accident conditions applicable to the plant. In this regard, considerable attention has been drawn to how such a demonstration should be performed.

In order to establish realistic and enhanced accident management guidelines, it is fundamental to promote sharing of the best current practices used to confirm the effectiveness of SAMGs. When SAMGs are in development, the technical accuracy and adequacy of the instructions and the ability of personnel to follow and implement SAMGs should be verified and validated. Even when SAMGs have been already in place, a periodic review is required to re-evaluate the changes in SAMGs made to reflect the current knowledge and plant conditions. The review also helps identify any potential gaps during the implementation of the guidelines, such as interfaces with EOPs and emergency plans, and responsibilities for implementing SAMGs, or any new information needed to diagnose the status of the plant during the accident. If changes are made to the guidelines, they should be re-validated to maintain their adequacy. This process plays a crucial role in ensuring that the accident management provisions in place will achieve the desired results.

The practitioners in the field of assessing SAM effectiveness have encountered various difficulties or challenges including those summarised below:

Challenge 1. Unlike design basis accidents during which the plant condition is diagnosed based on available plant parameters measured from reliable instrumentation, the plant condition during a severe accident is inferred from limited plant data with larger instrument errors. Such an inference, which may be supplemented by use of computational aids and/or engineering judgement, takes place with limited communication, lack of time and psychological stressors. As a result, it poses a challenge to accurately characterise the plant status and assess the feasibility of a SAM action, since the environmental conditions where the action is being carried out are not fully known or not available from reliable sources. Moreover, lack of data may cause serious difficulties in assessment of efficiency of the action being executed and of setting up proper timing and termination of the action.

Challenge 2. Certain equipment that is used during the execution of a SAM action is exposed to harsh conditions beyond its nominal operating range such as temperature, humidity, chemical environment and radiation exposure. In addition, for the specific equipment designed (or having capability) for severe accident conditions, there is no real possibility to test its reliability (this equipment remains in stand-by, likely for a long time) because of the impossibility to reproduce a test with severe accident conditions. Large uncertainties exist in

the survivability assessment of the equipment under severe accident conditions. Using this type of equipment (particularly that not designed for severe accidents) increases the degree of difficulty in demonstrating the feasibility and reliability of SAM measures.

Challenge 3. SAM takes an integrated, symptom-and-knowledge based approach involving the utilisation of available procedures and guidelines, equipment and instrumentation, human and organisational resources. A successful execution of a SAM action deeply depends on the performance of the SAM staff that consists of the lines of authority (the decision makers), the TSC staff (the evaluators), and the control room/operations staff (the implementers). Certain SAM actions are only viable for certain periods of time. Without understanding the time constraints suitable for execution of SAM actions, a viable action may be delayed, missing the opportunity to take the most effective action to arrest the accident progression and possibly resulting in undesirable effects. The time variable used to reflect the human and organisational performance (HOP) is another key factor challenging the assessment of SAM measures.

Challenge 4. A wide range of severe accident conditions, which correspond to a large number of possible permutations of how an accident may progress with and without operators' actions, are difficult and often impossible to represent in a realistic manner in the traditional verification/validation processes such as plant walk-throughs, emergency drills and exercises, and tabletop exercises. In addition, the real accident progression may permit certain equipment operable only in limited time periods, which compounds the difficulties in such verification/validation processes.

Challenge 5. Full-scope simulators enabling severe accident simulation are still under development and many NPP operators currently have no plan or intention for using such full-scope simulators. Some of the existing simulators generally lack the capability to simulate a wide range of plant-specific severe accident progression and the use of simulators not suited for representation of severe accidents may even lead to enforcing incorrect perceptions with regard to the accident progressions, uncertainty and timing of events.

The post-Fukushima follow-up activities, including those related to SAMG development, implementation and evaluation, have mobilised and are expected to continue to mobilise considerable attention and resources in the near future. It is thus important to summarise the best current practices including the use of analytical simulation to inform SAMG and actions, and make them available to the nuclear energy community.

In the current report, informing SAMG and actions through analytical simulation is meant:

“To supply the personnel who assess SAMG with supplementary information required to understand and characterise the SAM strategies and the associated implementing actions in such a way that the feasibility and efficiency of those actions under severe accident conditions can be assessed. The required information primarily comes from analytical simulations of severe accident progression with and without crediting the prevention⁴ and mitigation actions prescribed in the SAMG. Information from other sources including knowledge-based engineering judgement is also used in the assessment.”

This simulation-based assessment is helpful on three levels:

- Development or improvement of SAM strategies, principles and high-level actions
- Understanding of plant-specific capabilities and fission product barrier challenges

⁴ Prevention actions are used in a broad sense in this report and refer to those that prevent the accident progression or escalation (e.g. to prevent severe core damage prior to entry into SAMG or to prevent the failure of the reactor pressure vessel or containment after entry into SAMG).

- Preparation or readiness of specific actions in such a way that the feasibility and efficiency of those actions under severe accident conditions can be assured with reasonable confidence.

Diverse practices exist to conduct SAMG verification and validation using methods such as expert judgement, tabletop exercises, plant walk-throughs, emergency drills and exercises, full-scope simulators, field training, analytical simulations, and so on. Having described SAMG verification and validation in general and current practices in this regard, the WGAMA Task Group decides to take analytical simulation (e.g. deterministic and probabilistic analyses), which is one of the techniques that can be used to assess SAM effectiveness, for further discussion. Therefore, this report first provides an overview of the current SAMG status, regulatory requirements and guidance, issues related to SAM evaluation, recent Pressurised Water Reactor Owners Group/Boiling Water Reactor Owners' Group (PWROG/BWROG) generic SAMG updates, and current diverse practices related to SAMG verification and validation in the member countries. Then it focuses on the current toolsets, general methodologies and guidance on use of analytical simulation to inform SAMG and its specified actions.

Established severe accident analysis computer codes applicable for informing SAMG and assessing SAM actions are reviewed in Appendix B. Specific examples demonstrating the use of the guidance given in this report are provided in Appendix C. Examples of integrated assessments as part of SAMG validation using well-designed, full tabletop exercises supported by analytical simulations are given in Appendix D.

1. Introduction

This Working Group on Analysis and Management of Accidents (WGAMA) Task Group's focus is on documenting best practices and methods in regard to the use of analytical simulation to perform an assessment of the effectiveness of severe accident management (SAM) actions for the purpose of verification and validation of severe accident management guidelines (SAMGs). Analytical simulation when used with other methods can fully assess the mitigation features of the severe accident management guidance (SAMG). This Task Group provides solid basis and effective analytical techniques for use in this regard.

The Task Group recognises that the current computer codes for modelling of severe accidents have significant uncertainties despite advances in the knowledge of severe accident phenomenology in recent years. Additionally, the severe accident progression can be also affected by the plant system capability, availability of resources and operator actions. These factors result in a very large number of possible permutations of how an accident may progress. In recognition of this fact, this report also equally discusses the inherent limitations of the use of analytical simulations and simulation tools for assessing SAM effectiveness.

1.1 Objective

This WGAMA Task Group report:

1. Provides a basis for using concepts of “verification” and “validation” for informing SAMG and assessing the effectiveness of SAM actions.
2. Describes the existing practices aiming at assuring the correctness, usability and efficiency of SAM, such as tabletop exercises, emergency drills and exercises, full-scope simulators, plant walk-throughs, field training and analytical simulations.
3. Provides, in particular with the respect of the latter activity – analytical simulations, an overview of the national examples of past and ongoing assessments of the effectiveness of SAM actions through modelling of operator actions by severe accident analysis computer codes.
4. Discusses strengths and limitations of the analytical simulation techniques and tools.
5. Summarises the best and recommended practices with regard to the use of analytical simulations as one of the means to assess SAM effectiveness.

1.2 Scope

This WGAMA activity first describes the diverse current practices with regard to SAMG verification and validation. The second, and larger, part of the activity focuses on a specific technique, namely the use of analytical simulations of the impacts of operator actions on accident progression to inform and assess the SAM effectiveness. This approach is seen as providing valuable support for increasing confidence in SAM effectiveness [4]. However, it alone cannot be seen as sufficient for SAMG verification and validation.

Analytical simulation enhances our understanding of the SAMG-specified mitigation actions and associated plant response to a severe accident. Such simulations can be used to check the feasibility of the mitigation actions under foreseen severe accident conditions. The understanding comes from obtaining insights into specific steps of execution of an action that may require operators to use the available equipment and material resources. The feasibility check includes ability to identify necessity of execution of the action, together with identifying the constraints of the action for the time periods and environmental conditions under which the action is being carried out while ascertaining the positive and negative effects associated with the action. Most of the time, such a simulation activity is not expected to change the technical basis and overall SAM strategies that have been already established for an NPP, but the insights gained from the simulation may be used to identify new strategies or improve and refine the existing strategies, or plant design, if necessary.

On this basis, the Task Group proposes some general approaches and analytical methodologies that reflect the best and recommended practices for informing SAMG and actions.

This report does not cover other SAMG verification and validation aspects (see Section 3.2), including independent expert review of SAMG documentation, evaluation of staff SAMG training requirements and results, plant emergency drills and exercises, independent evaluation of SAMG exercises, and integration into an overall assessment of SAM effectiveness.

Level 2 probabilistic safety assessment (PSA) is one of the tools that can also be used to verify and improve SAM strategies. Although analytical simulation of SAMG-specified actions requires input from Level 2 PSA (e.g. the discussion given in Section 5.3.1), this report does not provide further guidance on use of Level 2 PSA for SAMG verification and validation. A recent draft report (IRSN-PSN-RES/SAG/2016-00159) by the European community under the Advanced Safety Assessment Methodology PSA Level 2 (ASAMPSA2) project documents some good practices and provides guidance on verification and improvement of SAM strategies with Level 2 PSA.

1.3 Expected users

The outcomes from the analytical simulations of SAM actions *in advance*⁵ provide insights into the timing, conditions and consequences of the actions being implemented, thus providing understanding of the actions themselves. The qualitative and quantitative information derived from the simulation is useful for the technical support centre (TSC) staff of the emergency response organisation to identify and evaluate viable prevention and mitigation strategies or actions. In this sense, the outcomes facilitate the decision-making process in the TSC.

The outcomes also help identify gaps or potential weaknesses in the existing SAMG, and in turn help improve or refine it. The utility personnel involved in development, implementation, execution and evaluation of SAM, as well as the regulatory staff performing reviews of SAM would benefit from the results of this activity.

The analytical simulations of key actions specified in a plant-specific SAMG and the associated documentation are useful as guidance or background information for training of personnel responsible for SAM and preparation of SAMG drills and exercises. The personnel involved in such activities would also make use of the simulation results.

⁵ Here, “in advance” means that such simulations should be performed as part of an SAMG evaluation. According to G. Vayssier [5], “*we should never leave our homework undone until a real event comes out*”.

1.4 Structure of the report

The background information, objective and scope of this WGAMA activity together with the expected users are given in Foreword, Executive Summary, and Section 1. Current regulatory SAM-related requirements and guidance, given by the International Atomic Energy Agency (IAEA) and the Western European Nuclear Regulator Association (WENRA) as well as used in the member countries, are summarised in Section 2. Section 3 provides an overview of evaluation of a SAM programme, describes the concepts of verification, validation, assessment of effectiveness in application to SAM, and discusses the concerns important to the assessment of SAM measures and the methods currently used for SAMG verification and validation. Section 4 summarises the current SAMG status and practices with respect to SAMG verification and validation in the member countries. Sections 4.3 and 4.4 summarise the generic pressurised water reactor (PWR) and boiling water reactor (BWR) SAMG updates recently conducted by Pressurised Water Reactor Owners' Group (PWROG) and Boiling Water Reactor Owner's Group (BWROG), respectively.

Pragmatic guidance for informing SAMG and actions through analytical simulations is presented in Section 5, including the descriptions of the current severe accident analysis computer codes used in severe accident simulations, general methodologies suitable for assessing SAMG-specified mitigation actions, documentation and use of the simulation results. Section 6 touches on PWR experience regarding the assessment of PWR SAMG with analytical support. Finally, conclusive remarks and commendable practices are given in Section 7.

More detailed and supporting information is compiled in appendices:

- Appendix A presents the survey questionnaire responses of the participants to this project, which are used as input in the preparation of this report.
- Appendix B compiles more detailed descriptions of the computer codes currently used in severe accident simulations, complementary to the brief descriptions given in Section 5.2.3.
- Appendix C provides examples of analytical simulations that demonstrate the use of the guiding principles and methodologies presented in this report for the assessment of SAM measures.
- Appendix D provides examples of SAMG validation through tabletop exercises while simulations of severe accident scenarios with operators' actions were used to guide the preparation and execution of the validation exercises.
- Appendix E provides more discussions, complementary to Section 3.3, on the concepts of verification and validation used in informing SAMG and assessing SAM effectiveness.

2. Regulatory requirements and guidance on severe accident management

Considerable efforts have been spent to advance severe accident phenomenological studies and severe accident management (SAM) measures in the past over two decades, although regulatory requirements and guidance for NPP licences to develop, implement, verify and validate severe accident management guidelines (SAMG) as part of an SAM programme vary from country to country.

Some nuclear regulations contain SAM requirements such as Swedish Radiation Safety Authority Regulatory Code SSMFS 2008:1.

“... documented guidelines shall have been drawn up at the facility for measures which may be necessary to implement in order to control and mitigate the consequences of beyond-design-basis accidents.”

“...verify that applicable safety aspects have been taken into account and that applicable safety requirements with respect to the design, performance, organisation and activities of the facility are met. The review shall be performed in a comprehensive and systematic manner and shall be documented.”

In some countries, SAMG was developed and maintained as a voluntary industry initiative (e.g. in response to U.S. NRC Generic Letter 88-20 dated 4 April 1990 [6]). In the United States, there is currently no regulatory requirement for SAMG with regard to its development, implementation, and maintenance; however, the Commission has recently directed the staff (see SRM-SECY-15-0065 dated August 2015 [7]) to update the Reactor Oversight Process to explicitly provide periodic oversight of industry's implementation of the severe accident management guidelines (SAMGs).

In response to an IAEA initiative to call for the development [8], implementation [9] and review [10] of SAM programmes for NPPs from 2003 to 2009 and the Western European Nuclear Regulator Association (WENRA) Reference Levels (2008 version) [11], many regulatory authorities had established regulatory guidance regarding the development and evaluation of SAMG to cope with the consequences of severe accidents. The lessons learnt from the Fukushima Daiichi nuclear accident led to further enhancing NPP defence-in-depth measures and strengthening the regulatory framework, particularly by stipulating regulatory requirements and guidance on SAMG development, implementation and evaluation. For example, a systematic SAMG evaluation is requested by France through the Operational Safety Review Team (OSART) mission every year since 2012.

The following are some examples related to regulatory requirements and guidance on SAMG.

WENRA Reference Levels (issued in September 2014 [12]), Issue LM:

LM1.1 A comprehensive set of procedures and guidelines, including emergency operating procedures (EOPs) and severe accident management guidelines (SAMGs) shall be provided, covering accident conditions initiated during all operational states.

LM2.3 SAMGs, with other specific procedures or guidelines when applicable, shall be provided to mitigate the consequences of severe accidents for the cases where the responses to events including the measures provided by EOPs have not been successful in the prevention of severe fuel damage.

LM3.3 SAMGs shall be developed in a systematic way using a plant-specific approach. SAMGs shall address strategies to cope with scenarios identified by the severe accident analyses.

LM4.1 The set of procedures and guidelines shall be verified and validated in the form in which they will be used in the field, as far as practicable, to ensure that they are administratively and technically correct for the plant, and are compatible with the environment in which they will be used and with the human resources available.

LM4.2 The approach used for plant-specific validation and verification shall be documented. The effectiveness of incorporating human factors engineering principles in procedures and guidelines shall be judged when validating them. The validation of EOPs shall be based on representative simulations, using a simulator, where appropriate.

LM6.4 Interventions called for in the set of procedures and guidelines and needed to restore necessary safety functions, including those which may rely on mobile or off-site equipment, shall be planned for and regularly exercised. The potential unavailability of instruments, lighting and power and the use of protective equipment shall be considered.

It is noted that WENRA Reference Levels (2008 version) [11] have been transposed into the Belgian legislation (Royal Decree 30/11/2011 art. 27 for Issue LM). Transposition of WENRA Reference Levels issued in September 2014 [12], including Issue LM, is in progress.

Canadian Nuclear Safety Commission (CNSC) regulatory guide G-306, *Severe Accident Management Programs for Nuclear Reactors*, issued in 2006, provided guidance for review and validation of SAMG. A new regulatory document REGDOC-2.3.2, *Accident Management*, has been developed and published in 2014 and revised in 2015 [13], which reflects lessons learnt from the Fukushima nuclear event and the current accident management insights and common views from international partners. In the CNSC REGDOC-2.3.2, licensees are required to “*develop, verify and validate accident management procedures and guidelines, including EOPs and SAMGs*”. REGDOC-2.3.2 also provides guidance regarding verification and validation of procedures and guidelines:

“The overall process of verification and validation should be formally documented. The level of documentation required will depend upon the complexity of issues addressed and the potential impact on safety.”

In the Czech Republic, the requirement on the verification and validation of SAMG is included in the Regulatory Guide LM-1.11 [14]. It follows WENRA recommendations. SAMG should be verified for completeness, correctness and readability. Plant-specific guidelines should correspond to actual plant state taking into account ongoing plant upgrades and safety enhancements. Guidelines should be validated with the aim to check the feasibility of actions, including technical and human factors. Alternative methods or their combination can be used for SAMG validation:

- full-scope simulator can be used to validate transition from EOP to SAMG or to validate SAMG if a full-scope simulator with such capabilities is available;
- desktop simulator or other analytical tool;
- expert judgement;
- emergency drills and exercises.

Supporting analyses for EOP and SAMG validation should be prepared using validated analytical tools. The best-estimate approach should be used. The regulatory guide also requires use of simulations and demonstrations for personnel training.

In Germany, general requirements for analyses to assess the effectiveness of SAM measures are described in the German new regulatory framework (after December 2012):

- *Analyses for representative severe accident scenarios are necessary and the application of appropriate analysis tools is demanded.*

- *The operability of each measure has to be demonstrated and has to be documented.*
- *For the fundamental safety function “Confinement of the Radioactive Materials”, the compliance with the radiological safety objectives (early release and large release shall be excluded, or their radiological consequences shall be limited) for level-of-defence 4b and 4c has to be demonstrated.*

In Japan, the development of emergency readiness is required under the Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors for coping with not only severe accidents but also extreme events. This includes personnel assignment, deployment of equipment, procedures, drills and exercises. The licensees in Japan are developing plant-specific SAM procedures as a part of their operational safety programmes in accordance with the above regulation. Basic requirements are issued as “the review standard for technical competence of required measures for prevention and mitigation of severe accidents”. Here, personnel assignment, preparations of procedures and implementation of drills are required based on individual plant conditions.

In Korea, SAMG for NPPs in operation was developed and implemented as per the “policy statement on severe accidents of nuclear power plants” (issued in August 2001 by the Korean government). The following statements are related to SAM:

- *Provide prevention and mitigation capabilities against severe accidents*
- *Establish Severe Accident Management Plan (SAMP) for all operating NPPs, covering strategies, organisations, SAMG, education and training, and analysis of instrumentation and safety critical information*

While the aforementioned “policy statement” is not in a legal requirement but an administrative order, SAMG shall be enforced into the regulatory requirement after June 2016, according to “Nuclear Safety Act” on Accident Management Programs for Nuclear Reactors that was legislated in May 2015.

The Finnish regulatory requirements and guidelines are specified in the guide YVL A6 and those pertinent to SAMG are given below:

715. *The severe accident management guidelines shall be based on the severe accident management strategy and the related analyses.*

717. *The procedures and guidelines shall be systematically validated and verified.*

In Spain, the legally binding regulatory instruction IS-26 (basic nuclear safety requirements applicable to nuclear installations) of Nuclear Safety Council (CSN) establishes that licensees must have operating procedures or guides for mitigating the consequences of beyond design-basis accident situations and they are also required to verify and validate procedures and to properly train all the personnel involved in their application. A new instruction IS-36 (Emergency Operating Procedures and Severe Accident Management), issued in 2015, translates to the Spanish regulation the WENRA Reference Levels for Issue LM (2008 version; the 2014 version will be incorporated in a future step).

Some international safety and regulatory authorities such as the Office of Nuclear Regulation of the United Kingdom emphasise on setting safety goals to measure the risk of postulated severe accidents from a nuclear power plant and developing expectations or guidance, rather than requirements, for severe accident management.

3. Concepts of verification, validation and assessment of severe accident management effectiveness

3.1 Introduction

This section first provides an overview of severe accident management (SAM) programme evaluation for an NPP and its subsequent evaluation of the severe accident management guidance (SAMG) package. Then, it touches on the concepts of verification and validation (V&V) with their definitions built on a basis of existing publications [8][9][15][16]. While these two concepts are closely related, their specific objectives differ. Appendix E of this report is an attempt to add clarity to these definitions using examples of the existing practices for SAMG V&V. The Task Group members agree that informing SAMG and actions through analytical simulation is part of SAMG V&V. In spite of the effort, different views still exist on using the definitions to claim whether informing SAMG and actions through analytical simulation is a validation or verification. Nevertheless, this WGAMA Task Group has recognised the notions of V&V and considers that the additional concept of “assessment of effectiveness” of SAM actions is more suitable for the context of this report. In the following, the term “assessment” is used as a general meaning covering also the V&V activities; when it is referred to the effectiveness evaluation of SAM, it is explicitly indicated as “assessment of effectiveness”. Therefore, assessment of effectiveness is defined and used in this report for processes involving analytical simulation as one of the means to assist in the assessment of SAM effectiveness. Finally, the different methods that can be used to inform SAMG and assess SAM effectiveness are briefly discussed.

3.2 SAMG – Key component of a SAM programme

An SAMG package is a key component of the SAM programme established for an NPP. The focus of this WGAMA Task Group is on informing SAMG and its actions through analytical simulation. Clearly, this activity contributes to the assessment of SAM effectiveness resulting from a plant-specific SAM programme. The established guidelines on the evaluation of a SAM programme for an NPP are documented in IAEA Safety Standard Series No NS-G-2.15 [8] and Services Series No. 9 [10], and thus not reiterated in this report.

However, it should be realised that a SAM programme evaluation includes an evaluation of the SAMG, which takes consideration of many aspects and activities including:

- **Independent expert review of the SAMG documentation.** The purpose of this activity is to assess the comprehensiveness and adequacy of a generic or plant-specific SAMG package. This activity includes reviews of the technical basis documents for the development of the SAMG and its implementation into the NPP application, all guidelines for diagnosing the plant condition, selecting and evaluating mitigation strategies and specific actions. The review may also cover the selection of reference instrumentation, instrumentation setpoints, and computational aids used to facilitate the evaluation and decision making, and enabling instructions for field operation to implement the selected mitigation actions.

- **Assessment of SAMG strategies and actions through analytical simulations.** This activity, which is the main topic of this report, can be part of the SAMG evaluation. Before the activity is carried out, it is essential to become familiarised with the SAMG documentation and understand the technical basis of the strategies and actions specified in the SAMG (e.g. by conducting the above-mentioned desktop review). The assessment provides additional support to the technical basis of the SAMG and contributes to SAMG verification and validation as well.
- **Evaluation of staff SAMG training requirements and results.** This evaluation is to assess the adequacy of the training requirements for the personnel responsible for execution of SAMG. The training requirements and the scope of the training provided are expected to be commensurate with their roles and responsibilities defined in SAM. This evaluation may also include a review of the organisational structures, communication and decision making protocols for SAM and emergency response.
- **Conduct of SAMG exercises including tabletop exercises, plant walk-throughs, and plant emergency drills and exercises, etc.** This activity is the responsibility of the NPP operator. Plant severe accident drills and exercises may involve on-site and off-site organisations, including emergency response teams. A full-scale plant severe accident drill/exercise tests the integrated response of SAM and emergency response crew to a postulated accident scenario. A plant drill/exercise may also test the integration of SAMG with other plant procedures (e.g. EOPs) and guidelines (e.g. Emergency Mitigating Equipment Guidelines (EMEGs⁶), FLEX Support Guidelines (FSGs), or Extensive Damage Mitigation Guidelines (EDMGs)). Where severe accident simulators are not available, the existing plant simulators (to cover pre-SAMG phase) together with additional computer code simulations of a selected severe accident scenario and expected operator actions are often used to guide the planning and preparation of the drill, and to control and execute the drill/exercise.
- **Independent evaluation of SAMG exercises.** The established plant-specific SAMG is often exercised in various ways including tabletop exercises, plant walk-throughs and group discussions with postulated severe accident scenarios. This type of exercises not only demonstrate how the SAMG documents are used by staff under a simulated stressful environment, but also obtain feedback from the users' points of view and identify areas for improvement. Hence, independent evaluation of SAMG exercises is a necessary activity of assessing the usability of the SAMG documentation. The evaluation may include other activities such as
 - **Observation of plant severe accident drills/exercises.** This activity is an important part of the SAMG evaluation. Plant drills/exercises simulating severe accidents not only provide training to the plant staff involving SAM, but also demonstrate the effectiveness of using the plant-specific procedures and guidelines such as SAMG to mitigate accident consequences and bring the accident into a controlled and safe state. Observation of drills/exercises helps assess the SAMG in an integral way such that the realism of the drills/exercises simulating severe accident scenarios, the usability of the SAMG documents, the field operability of the SAMG-specified strategies and actions, the human and organisational performance (HOP), and the overall effectiveness of SAM can be all assessed simultaneously.
 - **Review of SAMG exercise reports.** SAMG verification and validation activities such as tabletop exercises, plant walk-throughs, and plant drills performed are normally documented with the defined objective and scope of each activity together with identified strengths and areas for improvement. Review of those reports helps understand the scope or coverage of the SAMG verification and validation and thus evaluate the SAM programme as a whole.

6 See the Glossary given in this report for EMEGs, EDMGs, FSGs, etc.

- **Interviews or discussions with plant staff responsible for SAM.** This activity may require a site visit, which provides an opportunity to discuss the important aspects identified from the SAMG evaluation with the plant staff including the technical support centre (TSC) staff. The question and answer mode of discussions helps the assessment of the plant staff's familiarisation with the SAMG documents and their performance under severe accident conditions.
- **Integration of the above into an overall assessment of SAM effectiveness.** This is an overall evaluation in considerations of the results and feedback from all the above activities or other relevant activities related to SAMG verification and validation. Use of other measures such as those specified in EMEGs or FSGs for on-site and off-site supplementary or portable equipment and instrumentation should be considered in such an integrated assessment.

3.3 Discussion on verification, validation and assessment of effectiveness

SAM and the associated actions (e.g. specified in SAMG) should be verified and validated, to the extent practicable. Verification and validation are necessary to obtain reasonable confidence that the strategies and actions specified in SAMG can be implemented in the actual accident conditions and will achieve the intended results. The general concepts of verification and validation are well known and have been described in various publications. For example, the IAEA Safety Report Series No. 48 [2] has specified detailed processes used to verify and validate plant EOPs, for dealing with abnormal transients and design basis accidents.

However, guidance for SAMG verification and validation is less developed. Recently, NEA report NEA/CNRA/R(2014)2 [1] has discussed commendable processes for verification and validation of procedures and guidelines including SAMG using insights from the Fukushima Daiichi nuclear accident and consolidating the current views on accident management. The concepts of verification and validation discussed in this report are based on, and develop further, the views in [1] and other publications such as IAEA Safety Glossary [15], NS-G-2.15 [8], SRS-32 [9], and NEI 14-01 [16].

Verification

Verification refers to the technical accuracy and adequacy of the instructions. The verification process should confirm the compatibility of document instructions with referenced equipment, user-aids and supplies (e.g. portable equipment, posted job aids, strategy evaluation materials, etc.).

Validation

Validation refers to the ability of personnel to follow and implement the instructions. The validation process should demonstrate that the document provides the instructions necessary to implement the guidance.

Appendix E provides more discussion on key elements of verification and validation of SAMG.

Assessment of Effectiveness

The above-discussed concepts of verification and validation call for demonstrating the “technical accuracy and adequacy of the instructions” and “ability of personnel to follow and implement the instructions”. However, evaluation of the effectiveness of actions provided in the instructions (e.g. in SAMG) is not stressed or well described. In the subsequent discussions within this report,

Assessment of effectiveness refers to a process to confirm that the accident management actions help prevent the accident progression and mitigate/minimise the accident consequences to the public.

As pointed out in NEI 14-01 [16], there may be no “totally correct” decisions during SAM. An important component for establishing a process to assess SAM actions is to re-examine each of the key strategies and actions using plant-specific severe accident conditions in order to build-up our

understanding of the accident progression, elucidate key challenges to safety functions and fission product barriers, identify required preventing and mitigating actions and define their temporal and environmental constraints.

Assessment of SAM action effectiveness has the following specific objectives:

- gaining insight into the accident progression and consequences, and the impact on those from prevention and mitigation actions;
- quantifying action merits, advantages and optimum timing;
- ascertaining their potential negative impacts and identifying other actions to control the negative impacts;
- characterising the environmental conditions in the areas where a mitigating action is being executed such that its feasibility can be assessed;
- providing, or testing, pre-defined benefits and consequences from SAMG-specified actions to support the TSC operation, and feedback to SAMG refinement if necessary.

3.4 Focusing areas for assessing SAM actions through simulation

Analytical simulations of a severe accident progression with or without crediting SAMG-specified actions are one of the means that can assist in the assessment of SAM effectiveness. Informing SAMG and actions through analytical simulation may have a focus on addressing the following questions and concerns:

- **What are the success criteria and conditions to meet the objective of the assessment?** Defining what will be achieved is no doubt the first step of such an analytical undertaking. The objective should be set practically within the capability of the computational tool sets that are presently available, as well as in conjunction with the overall SAMG evaluation strategy and other verification/validation methods. Both the overall objective (e.g. assessing the effectiveness of a plant-specific SAMG) and the specific objective (e.g. assessing the feasibility of an action prescribed in the SAMG) should be clear to the staff who perform the assessment. Once the assessment objectives are clearly defined, the criteria and conditions that are used to measure the success of the assessment should be identified.
- **What is the impact of an earlier or later initiation of a prevention or mitigation action?** Some prevention or mitigation actions permit for a range of time delays to be feasible and effective. For example, running a recirculation pump to cool the moderator water in a CANada Deuterium Uranium (CANDU) reactor is better initiated before massive core debris has developed in the calandria vessel to prevent the accident progression. Gaining the knowledge of sensitivity of the action to time complements the existing SAMG technical basis and helps the TSC staff to consider the timing effect on the selection of viable prevention or mitigating actions during SAM.
- **What are the environmental conditions associated with the execution of the action?** At the time when a prevention or mitigating action is called for, knowing the relevant environmental conditions (e.g. water level, temperature, pressure, presence of debris and non-condensable gases, etc.) is crucial to assess if the action could be initiated. After its initiation, knowing the environmental conditions relevant to the execution of the action is also essential to assess if the action can be sustained to achieve the intended outcome, and will not be interrupted prematurely by any unanticipated conditions such as a pump stall due to presence of debris in the flow path.

- **What are positive outcomes resulting from the action?** This is to confirm that the anticipated benefits resulting from executing the action can indeed be achieved. The comparison between the simulations with and without crediting the action can provide quantitative evidence on the merit of the action, e.g. in terms of reduction in containment pressure and hydrogen generation.
- **What are negative outcomes resulting from the action?** This is to evaluate risk of potential negative effects resulting from executing the action. A comparative assessment by simulations with or without crediting the action could confirm and quantify the negative effects that may have been already identified during the SAMG development when expert judgement was largely used. It could also help identify any potential new unfavourable factors or disadvantages when the effects of the action are simulated and examined in detail. If necessary, the simulation may lead to identifying additional actions to control or minimise the recognised negative effects.
- **What is the outcome of an overall evaluation regarding the robustness of the action?** This is to integrate all the above into an overall evaluation of the action. One of lessons learnt from the Fukushima Daiichi accident, which has been implemented in the recently updated NS-G-2.15 [8], is SAMG's robustness against contingency caused by equipment, infrastructure, human factors, and natural hazards. The simulations provide environmental conditions under which the action is being implemented. Obtaining those conditions allows the feasibility and robustness of the action to be assessed.

3.5 Methods of SAMG verification/validation and effectiveness assessment

This section provides a general description of methods that can be used to verify/validate and assess SAM effectiveness. Input to this section comes from the participants' response to Question 4 of the survey (see Appendix A):

What approaches (method or combination of methods, tools, data and computational aids, evaluation criteria, etc.) are, or will be, used in your country or organisation for SAMG verification and validation in general, and for assessing the feasibility of SAMG-specified actions in particular?

There are many methods that are currently used or will be used to assess SAM effectiveness, including:

- **Tabletop exercise method** is a method whereby personnel explain and discuss the strategies and steps given in the SAMG in response to a scenario and accident progression. In certain practices, this method is made of multiple steps such as preparation, exercises, feedback and documentation. Appendix D provides examples of tabletop exercises.
- **Technical experts/board judgement plus deterministic analyses using computer code simulations** is a method of technical expert judgement combined with reviews of supporting analyses using computer codes to assess SAM strategies or as part of SAM validation. The identified strategies for preventing/mitigating severe accidents are assessed by technical experts, the SAMG vendor, and/or regulators whereas simulations of severe accident progression and consequences using computer codes are reviewed and used to confirm the adequacy of the strategies.
- **Plant walk-through method** is a method whereby personnel conduct a step-by-step enactment of their actions without carrying out the actual control functions. This includes equipment access and equipment staging when required.
- **Plant drill/exercise simulating a severe accident** is a method used to test the capability of the personnel involved in SAM to use the specified procedures and guidelines and provide response to a simulated plant condition. The scope of the drill/exercise and the extent of use of SAMG are

constrained by many factors including selection of a severe accident scenario for the drill. In some utilities, the coverage of SAM validation for NPPs is augmented by conducting multiple drills/exercises per year, which are organised either at a local or national level.

- **Safety review plus supporting calculations** is a method used to assess SAM effectiveness under the framework of the periodic safety review. With this method, safety authorities or their delegates evaluate plant-specific SAM strategies by reviewing the current SAMG documentation and supporting calculations/simulations of severe accident scenarios and by observing tabletop exercises, plant walk-throughs, plant drills and exercises that simulate severe accident scenarios. Areas of improvement identified from the review and validation exercises are then considered in updating the SAMG.
- **Analytical simulation** is a method used to assess the important components of SAMG, particularly its pre-determined strategies and prevention/mitigation actions. With this method, the focus areas that need to be assessed are given in Section 3.4 above. First, the assessment requires a check of knowledge related to severe accident phenomenology, plant equipment and instrumentation, analytical tools and their qualification, plant input file development and testing, user experience/qualification and collaboration with computer code developers, and results evaluation and interpretation. Then, the SAMG assessment process using the analytical approach may be implemented by multiple steps: for example, defining success criteria for analysis, developing simulation matrix, performing analysis, evaluating and documenting the impact with or without crediting SAMG-specified actions. This method is further elaborated in Section 5 of this report.
- **Simulator training** is a method by which control room operators perform control functions on simulator equipment according to a scenario [4]. At present, the development of full-scope severe accident simulators is still ongoing in many member states. For example, a plant-level severe accident simulator has already been installed in Korea, KORI unit 1, but currently it can offer only limited accident scenarios and operators' actions. For BWRs only two plants have full-scope simulator capability for severe accidents (Monticello and Perry), which is limited to only in-vessel severe accident modelling based on MELCOR. Full-scope severe accident simulators exist at Krsko (Slovenia) and Ringhals (Sweden). Simulators have been upgraded based on MAAP to cover severe accident conditions at Olkiluoto 3 (Finland), Ling Ao phase 2 (China), and Susquehanna (USA). EDF (France) is planning to equip the EPR simulator for new nuclear projects with severe accident capabilities, via the integration of MAAP.
- **Combination of different methods and tools** is an approach to applying a number of methods and tools to assess SAM effectiveness. The methods mentioned above, including those involving staff training in SAM equipment and review of training results, could all be considered. Useful tool sets include tabletop exercise, qualified computer codes, computational aids, PC-based or full-scope simulators.

It should be noted that, except for the last bullet, each of the methods being discussed above is characterised with apparent strengths and limitations, and using a method alone may be insufficient to assess the effectiveness of SAM.

A verification and validation team should include experienced personnel in various fields of expertise such as: plant operators, simulator instructors, experts in severe accident modelling, emergency responders, and human factors experts. Generally, the members of staff involved in the validation of SAMG should not be those who developed the SAMG [8]. If the SAMG developers are involved in actual validation, it is desirable to limit and specify their roles to allow the validation activities to be carried out independently.

When developing validation scenarios the goal is to exercise procedures, guidelines, enabling instructions, transitions and communications to the extent possible. It is not expected that drills and exercises will cover every conceivable scenario with realistic timing and operator interaction.

4. Current SAMG Status and Practices for Informing SAM Effectiveness

4.1 Introduction

The purpose of this section is to summarise the current status of severe accident management guidance (SAMG) and current diverse practices for informing SAMG and actions to assure severe accident management (SAM) effectiveness. To achieve this, a set of questions were prepared, reviewed and approved by the Task Group and then the questionnaire (see Appendix A.1) was sent to all the participants of this project for collection of input to this report. The questionnaire consists of five sets of survey questions that cover the following topics:

- a) Regulatory requirements and guidance on SAMG
- b) Generic or plant-specific SAMG
- c) Status of SAMG implementation and evaluation
- d) Methods and tools used for SAMG verification and validation
- e) Commendable practices and examples of analytical simulations

The detailed responses of the participants of this project to the questionnaire are recorded in Appendix A. The responses to items (a) and (d) are used as input to Section 2 and Section 3.5, respectively. This section summarises the responses to items (b) and (c). Item (e) is further reflected in Sections 5, 6, and 7.

Recent updates on generic pressurised water reactor (PWR) SAMG and boiling water reactor (BWR) SAMG to incorporate lessons learnt from the Fukushima nuclear event are described in Sections 4.3 and 4.4, respectively.

4.2 Summary of individual responses to the survey questionnaire

Belgium

Answers provided by Tractebel Engineering (GDF Suez).

The severe accident management guidelines (SAMGs) for the Belgian units were implemented during the 1990s. The Tihange NPP in Belgium has implemented Westinghouse Owners' Group (WOG) SAMG with plant-specific implementation, whereas the Doel NPP have implemented a utility-developed SAMG, further developed and inspired by the Westinghouse approach. The SAMGs have been validated and are presently being revised to integrate the experience feedback from the Fukushima accident. The validation was performed in the framework of the Periodic Safety Review and a validation scheme was created around nine severe accident scenarios (see Appendix D) which were defined and selected based on WOG SAMG templates. The validation has been performed for both full power operation and shutdown conditions and MELCOR 1.8.5 pre-calculations have been used for assessing the plant response during the validation of SAMG.

Canada

Answers provided by the Canadian Nuclear Safety Commission (CNSC) as well as CANada Deuterium Uranium (CANDU) Owners' Group.

The SAMG for the Canadian NPPs follows the approach of WOG, taking into account the features of the CANDU reactor design and its characteristics of severe accident phenomenology. Based on the generic SAMG, each nuclear station developed station-specific SAMG and technical basis, taking into account station-specific design features and instrumentation. Presently, and in the light of the Fukushima accident, the existing SAMG implementation programme is accelerated and the scope of SAMG is expanded to include multi-unit and irradiated fuel bay (IFB) events. The Canadian regulatory body has initiated analytical simulation of SAMG-specified actions to inform SAM effectiveness. The Canadian utilities have conducted some limited simulations to support SAMG development and updates, but have not done simulations for the purpose of assessing feasibility and efficiency of SAMG actions. However, the Canadian utilities have conducted tabletop exercises to verify the usability of SAMG documentation and plant drills/exercises to demonstrate the effectiveness of SAM. From the Canadian side, simulation of SAMG-specified actions to understand their associated environmental conditions and assess their feasibility and efficiency is a commendable practice for informing SAM effectiveness.

Czech Republic

Response by ÚJV Řež, a. s.

The Czech NPPs Dukovany and Temelín have implemented SAMGs developed in a collaboration of the TSO ČEZ with Westinghouse, and based on the WOG generic SAMGs. The first plant-specific SAMGs were implemented around the year 2000 for full power conditions. Presently the SAMGs are being updated and extended to shutdown states including severe accident conditions in the spent fuel pool. Also, following 2011, improvements have been identified and many hardware modifications are under implementation. Validation of SAMG was launched in 2003 and followed a matrix of validation analyses. The validation process consisted of i) definition of success criteria, which can be common (e.g. achievement of stabilised state) or specific to a certain SAMG; ii) development of a validation matrix; iii) analysis of basic scenarios (without SAM action) and of variant scenarios with SAM action, using codes like MELCOR and ASTEC; and iv) evaluation of SAMG application impact.

As a demonstration of commendable practices, two examples of analysing SAM actions within a base case and alternative variant scenarios are provided in Appendix A.4. They support a critical discussion of the benefits and negative impacts.

Finland

Response by VTT, Fortum, and TVO.

The Finnish NPPs have implemented SAMG, which is a regulatory requirement. For Loviisa NPP, the SAMG has been developed by the utility and includes SAMG for the backfitted in-vessel retention (IVR) system. Olkiluoto 1&2 also have utility-developed SAMG, which were implemented together with the SAM mitigation system in the beginning of the 1990s. The regulatory ("success") criteria for SAM are: i) no release larger than 100 TBq of Cs-137; ii) no immediate large-scale evacuation of the population; and, iii) Severe Accident Safe State is reached. The scope for the SAMG has been reviewed in 2008 for OL1 and OL2 in conjunction with the Periodic Safety Review and after March 2011 as part of the national and European NPP stress tests. SAMG and emergency operating procedures (EOP) are updated by NPPs based on plant modifications and in addition they are checked every 4 years.

Major areas of the SAM strategies, such as IVR and controlling of containment pressure developed, (e.g. for Loviisa) are validated against experimental data. Success of the SAM has also been simulated

with suitable computer codes such as APROS, COCOSYS and MELCOR. For the future, it is planned to simulate severe accidents with an APROS-based full-scale simulator.

France

Response by EDF.

The French NPP fleet have SAMGs developed by EDF, with each NPP applying them with only minor necessary adaptations. These SAMGs are reviewed during each Periodic Safety Review. The SAMG design has a phenomenology approach. For each severe accident risk (e.g. high pressure vessel rupture, hydrogen, corium management. etc.), dedicated calculations have been performed mainly with the MAAP software. There is no formal criterion for SAM success, but the common objectives of SAM of maintaining containment integrity and of limiting radioactive releases are pursued. The SAMGs are validated during a large number of drills/exercises that are organised at either national or local level.

Germany

Answered by GRS mbH (Technical Safety Organisation) for the status-quo of German Nuclear Power Plants regarding severe accident management.

In Germany, SAMGs have been a regulatory requirement from the year 2012 and have been implemented in all operating NPPs since then. The SAMGs have been developed by AREVA. The general success criteria for the SAMGs are the avoidance of reactor pressure vessel (RPV) failure and, if entering the ex-vessel phase, the sustainment of containment integrity and the minimisation of radionuclides releases. Requirements for assessing the effectiveness of SAM actions are: i) use of appropriate analysis tools; ii) demonstration and documentation of the feasibility of each measure; and, iii) demonstration of the compliance of the confinement of radioactive materials with the radiological safety objectives (exclusion of early and large releases, or limitation of their radiological consequences). Effectiveness of SAM is further to be demonstrated by the survival of containment integrity and the operability of systems supporting this goal, e.g. filtered containment venting.

For the assessment of SAMG by deterministic safety analyses, the vendor, TSOs of the regulators and GRS are using thermal-hydraulics codes and severe accident analysis codes. In addition, detailed analyses are performed to assess single phenomenon important to severe accidents.

Japan

Response by Regulatory Standard and Research Department Secretariat of Nuclear Regulation Authority (S/NRA/R).

Before the Fukushima Daiichi accidents, operation procedures under accidents were prepared by the industry. Japan Nuclear Energy Safety Organization (JNES) reviewed those procedures of representative plant types. After the Fukushima Daiichi accidents, the new safety regulation requires provision of emergency readiness against not only severe accidents but also extreme events based on individual plant conditions. This includes preparations of personnel assignment, deployment of equipment, development of procedures, implementation of drills/exercises and periodical check. How these elements will be implemented in the operational safety programmes is reviewed as a technical competence.

Requirements include common items, recovering works, supporting activities, providing procedures, training and organisation for prevention and mitigation. Securing habitability of main control room (MCR) and emergency response centre (ERC) and communication under severe accidents are also required.

In the licensing, entire readiness and individual elements are verified by appropriate approaches. Simulations tools are a complementary approach that is widely applied in assessing effectiveness of SAM procedures under typical scenarios. As an industry standard, the Atomic Energy Society of Japan

(AESJ) developed, “Implementation Standard Concerning Preparation, Maintenance and Improvement of Severe Accident Management in Nuclear Power Plants” (AESJ-SC-S005). In this document, typical approaches are exemplified as: a) plant walk-down and periodical drills/exercises; b) tabletop exercises and plant simulator exercises; c) operational trainings; d) review of training results and surveillance of equipment inspection results. Validation is performed independently by: i) the organisation (section) in charge of procedures; ii) persons who are not involved in developing procedures; and iii) third parties.

Korea

Answers provided by Korea Atomic Energy Research Institute (KAERI).

In Korea, all the plant-specific SAMGs for nuclear power plants (NPPs) in operation were developed and implemented as per the “policy statement on severe accidents of nuclear power plants” issued in August 2001. While the aforementioned “policy statement” is not a legal requirement, but rather an administrative order, the SAMG has been enforced into the regulatory requirement in June 2016, according to “Nuclear Safety Act” on Accident Management Programs (AMPs) of Nuclear Reactors that had been legislated in May 2015, for the purpose of strengthening regulation of severe accident management with the legal basis after the Fukushima accident.

For each type of plant in operation (PWR and PHWR), the corresponding generic SAMG was first developed based on the WOG Generic SAMG and thereafter plant-specific SAMGs. After the Fukushima accident both Shutdown SAMG (SSAMG) and Integrated SAMG (ISAMG, covering both Full Power SAMG and SSAMG) have been developed for all the operating reactors and completed in December 2015. The periodic updates of the SAMGs reflect the plant-specific PSA results, and accident analyses for the representative scenarios have been performed with the MAAP code for PWR type and the ISAAC code for CANDU type.

Relating to assessment of SAM effectiveness, the operator’s actions have been assessed for most plants to determine if they are realistic and effective, and if the guidelines really enhance the plant’s capability to handle severe accidents in terms of mitigating the negative impacts of each action in the accident progression. A tabletop exercise (or discussion) method is used for the SAMG validation, which is typically made of four steps: a) preparation of validation material, b) validation exercises, c) validation feedback, and d) validation documentation. Then the validation process is implemented by a validation team that plays a technical support centre (TSC) role and a main control room (MCR) role, in a plant simulator room which provides the same environmental condition as the MCR. The evaluation of most SAMGs in Korea has been made through severe accident analysis for the representative accident scenarios, which have been chosen based on the PSA results. For each reactor type, more than two accident scenarios are chosen so that most strategies and actions in SAMG can be validated through them.

Mexico

Answers provided by National Commission of Nuclear Safety and Safeguards (CNSNS).

In Mexico, the current SAMG for the Laguna Verde NPP are the generic Boiling Water Reactor Owner’s Group (BWROG) SAMG adapted to the plant-specific configuration. This SAMG is under a revision and improvement process performed by the operator according to their SAMG implementation schedule and, once finished, will be reviewed by nuclear regulatory body. For this purpose CNSNS is working on an internal guideline for an SAMG review process and will utilise MELCOR to evaluate the feasibility of the identified strategies in order to provide inputs for SAMG’s effectiveness for Laguna Verde NPP. Evaluation criteria for SAMG is currently not in use but will be defined in the near future.

Slovak Republic

Answers provided by the Nuclear Power Plant Research Institute (VUJE).

The SAMGs in the Bohunice and Mochovce NPP are plant-specific SAMGs that have been developed based on WOG generic SAMG. The specifics of these SAMGs reflect existing hardware devoted to SAM. The SAMGs have been implemented using an iterative process. In the first step generic SAMGs are being developed mainly to be a basis for the plant modifications. After this first step some site specific systems and mitigation measures are implemented at the units. The SAMGs are then adjusted for the upgraded condition. In the validation and verification process the MELCOR code and experience from implementation of existing SAMGs in Slovak NPPs and the expertise of EOPs and SAMG experts, national and foreign, has been used. An identified commendable practice is that a real-time severe accident simulator would allow better identification of the time dependencies while mitigating particular scenarios. Missing guides and proper regulation of the validation process is considered as a deficiency; however, such a deficiency was healed via co-operation with Westinghouse and adaptation corresponding Westinghouse methodologies.

Spain

Answers provided by the Nuclear Safety Council (CSN).

Spanish plants can be grouped in three main groups according to their technology: PWR-Westinghouse, BWR-GE and PWR-Siemens-KWU. In the case of Westinghouse and GE plants, generic SAMG issued by the respective owner's groups (PWROG for Westinghouse and BWROG for GE) have been used as the main basis for SAMG development. Plant-specific SAMG results from the adaptation of generic SAMG taking into account plant-specific information. Recalculation of some limits, curves and other elements are the main differences between generic and specific SAMG. In principle, the structure of the generic SAMG has been maintained.

In the case of Trillo NPP (PWR-Siemens-KWU) the development of plant-specific SAMG has been done also on the basis of generic guidelines used in German plants and a similar adaptation process has been followed.

All the Spanish plants have implemented an EOP-SAMG system. SAMG implementation has been done in two phases and SAMGs are today fully operative. Limited assessment of the adequacy and effectiveness of SAMG-specified actions has been performed as a part of the adaptation process of the generic guidelines. However, most of the assessment activities have focused on the feasibility aspects of the guides. These activities have been performed by the licensees and audited by CSN.

Review and evaluation of SAMG documents, including specific actions, is under the responsibility of the licensees. To this aim, they often look for external support from SAMG developers or from engineering support organisations. In addition, CSN controls the general process and performs inspections on specific points of the guides.

Sweden

Answers provided by the Swedish Radiation Safety Authority and Forsmark, Oskarshamn and Ringhals NPPs.

Sweden has in total 7 BWRs and 3 PWRs in operation. For the Westinghouse PWRs, PWROG SAMG has been implemented with plant-specific modifications (filtered containment venting system, passive autocatalytic recombiners, etc.). For the BWRs of Swedish ASEA-Atom design there are "SAMG-like" handbooks developed by the three utilities (Forsmark, Oskarshamn and Ringhals) respectively. These handbooks are centred on the implemented SAM mitigation systems such as filtered containment venting, water-filling of the lower drywell, operation of independent containment spray, etc.

Based on the outcome from the ENSREG stress tests, all of the SAMGs and handbooks are updated accordingly. Validation on SAMG specific actions at Forsmark is done through evaluations performed by the Operation Department and by plant walk-throughs on a case-by-case basis. Work is ongoing to expand this validation activity. At Oskarshamn, MAAP is used for verification. Since 2014, Ringhals 2 has a MAAP5 Severe Accident Simulation capability built-in in the simulator. This has not yet (Nov 2014) been utilised but may be useful in the future.

United States

Answers provided by the US Nuclear Regulatory Commission (NRC).

In the US, SAM is a voluntary industry initiative for operating power reactors and SAMG is an industry product. In the aftermath of Fukushima, there has been an increased attention within the industry to revisit the existing SAMGs and to perform necessary revisions taking into consideration lessons learnt from Fukushima. Likewise, there has been an increased attention within the regulatory organisation (NRC) to consider the merit of some form of regulatory oversight with regard to SAM. The development, improvement, and implementation including verification and validation of SAMG still remain as industry initiatives. The Commission has recently instructed the staff (see SRM-SECY-15-0065 dated August 2015 [7]) to update the Reactor Oversight Process to explicitly provide periodic oversight of industry's implementation of the SAMGs.

The most notable change in PWR SAMGs is the integration of three separate SAMGs into a single generic SAMG while retaining adequate flexibility in the integrated guidance document for use by different plant designs. For the BWR SAMGs some of the more significant severe accident guidelines changes under consideration include: 1) revision of flooding strategy; 2) guidance for anticipatory containment venting (pre-core damage); 3) secondary containment hydrogen control; 4) spent fuel pool control; 5) computational tools; and 6) main control room implementation of Severe Accident Guides (SAGs). The verification and validation procedures are described in industry's document, "Emergency Response Procedures and Guidelines for Beyond Design Basis Events and Severe Accidents," (NEI 14-01) [16].

4.3 PWR generic SAMG update by Pressurised Water Reactor Owners' Group

4.3.1 Background

Following the Fukushima accident, numerous industry activities were initiated to implement lessons learnt. Within the context of SAMG, a number of industry and regulatory programmes were initiated. In particular, the Pressurised Water Reactor Owners' Group (PWROG) began working on "Support for Development of Enhanced SAMG Technical Basis," to support the update of the Electric Power Research Institute (EPRI) Technical Basis Report (TBR), which serves as the basis for SAMG strategies. Subsequently, the PWROG carried out a programme entitled "Development of Enhanced SAMG," which is in the process of developing a major revision to the generic SAMG, including lessons learnt as well as integration of different SAMG approaches.

The ongoing programme "Development of Enhanced SAMG,"⁷ was split into two phases [18]:

Phase 1: Update current generic SAMG: Westinghouse (W), Combustion Engineering (CE) and Babcock & Wilcox (B&W). Updating each of the three SAMG (W, CE and B&W) to address EPRI TBR updates including strategies for mitigating spent fuel pool (SFP) fuel damage was completed in January 2013. The updated generic SAMG will be issued to utilities for plant-specific implementation.

7 France is also in the process of developing revisions to SAMGs. After the Fukushima accident, the nuclear power plants in France have been provided with additional equipment and instrumentation to increase their capabilities for severe accident prevention and mitigation.

Phase 2: Develop consolidated PWROG SAMG. The Phase-2 work is scheduled to be completed by January 2016. The work scope includes

- implementing lessons learnt from Phase 1;
- considering best practices from each of the existing W, CE and B&W SAMGs;
- addressing operational changes for other Fukushima lessons learnt;
 - enhanced equipment capabilities (e.g. use of Extensive Damage Mitigation Guidelines (EDMGs) and FLEX equipment after core damage);
 - interfacing with enhanced procedures or guidance (e.g. extended Station Blackout);
 - including SAMG for multi-unit sites;
- addressing lessons learnt from user feedback;
- co-ordination of SAMG with Emergency Operating Procedures (EOPs) and EDMGs;
 - development of appropriate kick-outs from EOPs to SAMG;
- ongoing discussion for entry to SAMG for any new procedures and guidance;
- development of appropriate guidance for command-and-control transitions consistent with transfer to SAMG;
- development of guidance for the use of all installed and portable equipment.

4.3.2 *PWROG SAMG Key structural changes*

Additional control room actions

One of the more significant changes that have been made to the SAMG control room guidance was to allow the control room staff to implement certain strategies that have insignificant negative consequences without evaluation by the technical support centre (TSC) staff. There are four main “Priority Actions” that were identified for the control room to implement prior to checking to see if the TSC is ready to take command and control of the accident.

1. Inject into the Steam Generators (SGs)
2. Depressurise the Reactor Coolant System (RCS)
3. Inject into the RCS
4. Inject into containment (without operating containment sprays)

This change allows the control room to take action without the need for an in-depth evaluation of the actions. These actions have sufficient technical basis already developed to support their implementation from the control room without the need for TSC concurrence.

Diagnostic process guide

To effectively choose the appropriate actions and to prioritise the implementation of the actions, diagnosis of the plant conditions is needed. The Diagnostic Process Guideline (DPG) provides this function and navigates the user in the TSC through the PWROG SAMG via plant parameter values and trends determined to be important to selecting a mitigation strategy. This change allows for the consolidation of the Diagnostic Flow Chart (DFC), Severe Challenge Status Tree (SCST), Severe Accident Exit Guideline (SAEG)-1 and SAEG-2 all into a single guidance document. A draft version of the Parameter Worksheet in the DPG for Westinghouse plants is shown in Figure 1 on the next page.

Action based TSC guidance

As part of the feedback that the PWROG gave the SAMG developers, it was noted that during SAMG drills/exercises it was not uncommon for differences of opinion in the TSC to lead to decision “lock-up” on certain SAMG topics. This was mostly due to the sometimes vague implementation guidance that also required a detailed review of the benefit and consequence information related to implementing a strategy. It was subsequently determined that much of the weighing of benefits and consequences can be done by the severe accident experts who are writing the SAMGs and a recommended action for most scenarios can be developed. The details of the changes that were made to the Severe Accident Guides (SAGs) include:

- moving the benefit-consequence information to a Technical Support Guide (TSG) that can be consulted if deviating from the SAG guidance or if additional information is needed on why a particular strategy is recommended;
- giving separate, more specific guidance steps depending on certain pre-defined accident characteristics;
- including a “Left Hand Page” that corresponds to each SAMG step (which is presented on the right hand page in the TSG) to explain the basis at a high level to ensure guidance steps are applicable to the ongoing accident.

However, this does not preclude the need for knowledge-based accident management. The SAMG user is expected to exercise judgement and use a technical support guideline to assess benefits and negative consequences if there is any question about the appropriate strategy to recommend.

Instrumentation guidance

Four additional Technical Support Guidelines (TSGs) have been developed for the PWR SAMG. The first TSG is the Instrumentation Guideline. The purpose of this support guideline is to provide assistance for the determination of the validity of instrumentation indications and to identify potential alternate means of establishing key plant parameters while using the SAMGs. This TSG adds significant value in the area of managing uncertainty in instrumentation response during a severe accident as well as loss of all instrumentation. The Instrumentation Guideline TSG captures instrumentation guidance for all of the key plant parameters that need to be monitored in the SAMGs. This guideline allows SAMG evaluators to determine the validity of instrumentation readings for the DPG by confirming:

- primary and secondary instrumentation in agreement;
- correction factors have been properly applied;
- instrumentation readings are within reliable range based on readout and environmental conditions;
- instrument response is in the expected direction based on accident progression and implemented strategies.

For each parameter that is examined by this TSG the following information is pre-filled for the individual plant that it applies to:

- primary purpose;
- methods of measurement (primary, secondary and alternate indications);
- impact of severe accidents on instrumentation;
- expected instrumentation response to accident conditions;

- indicated and useful range;
- expected response to various actions;
- expected response based on other parameters.

Multi-unit site impacts

In order to account for multi-unit accidents several changes to the SAMGs were made. There was not one single guidance document or one specific change that was made to address the issue of multi-site impacts. This issue spans many areas of the SAMG and as such several changes were required. The following areas were adjusted to account for multi-site complications:

- Addition of the decision maker TSG

This change allows for guidance to be issued from a higher level perspective of the SAMGs. This TSG includes other site-wide concerns as well as the TSC recommended strategies. For sites where multiple units are in an accident scenario the decision maker may be forced to make decisions on where to deploy a single resource for example. The Decision Maker TSG includes guidance for the decision maker to consider many factors when making this type of decision.

- Addition of the site capability TSG

The Site Capability TSG includes all of the equipment that is available to respond to a severe accident throughout all the units on a particular site. This enables TSC staff to have a more complete picture of the entire site and the resources that are available to respond to a severe accident.

- Including the potential negative consequences of using resources from another unit

This type of information is included in the benefit consequence TSG to reinforce the relationship between all the units on a particular site.

4.3.3 Generic SAMG validation

The generic PWROG SAMG was validated at 3 US plants, one of each nuclear steam supply system (NSSS) type (Byron Station – Westinghouse NSSS, Three Mile Island – B&W NSSS and Palo Verde – CE NSSS). Each validation drill/exercise was executed in three major steps:

- Pre-drill briefing: A pre-drill/exercise briefing by the lead controller provided the participants and observers with the plant conditions for the start of the drill/exercise.
- Drill/exercise scenario: The postulated scenario is presented as the drill/exercise continues.
- Debrief: Following the end of the drill/exercise, an immediate debrief was conducted by the controllers. The utility participants offered their insights first, followed by the controllers and finally the observers. The lead and data controller facilitated the feedback and captured the insights deemed appropriate by the entire group. These are logged as observations; all observations were reviewed by the PWROG SAMG Core Team and dispositions to all observations are being included in the final PWROG SAMG.

Figure 1: A sample parameter worksheet used in the diagnostic process guideline (DPG) for an updated PWR SAMG

		Highest Priority				Lowest Priority				Monitor and Address SFP in Parallel							
DATE:		SG Level Initiate SAG-3		RCS Pressure Initiate SAG-4		Injection Flow Rate Initiate SAG-5		Containment Water Level Initiate SAG-6		Containment Hydrogen Initiate SAG-7		Containment Pressure Initiate SAG-8		Site Release Level Initiate SAG-9		SFP Water Level Initiate SAG-10	
TIME:																	
Setpoint																	
Actual																	
RED																	
ORANGE		ANY LESS THAN [Le01]		GREATER THAN [Pr04]		LESS THAN [Fr03]		LESS THAN [Le07]		SEVERE CHALLENGE		GREATER THAN [Pr17]		LESS THAN [Ra03]		LESS THAN [Le13]	
Actual																	
YELLOW		ALL GREATER THAN [Le01] and ANY LESS THAN [Le05]		BETWEEN [Pr04] and [Pr03]		BETWEEN [Fr03] and [Fr04]		FLAMMABLE OR FUTURE FLAMMABLE		FUTURE SEVERE CHALLENGE		BETWEEN [Pr16] and [Pr16]		BETWEEN [Ra03] and [Ra02]		BETWEEN [Le13] and [Le14]	
Actual																	
GREEN		ALL GREATER THAN [Le05]		LESS THAN [Pr03]		GREATER THAN [Fr04] OR TSC Judgment		GREATER THAN [Le07]		NO HYDROGEN CONCERN		BETWEEN [Pr13] and [Pr13]		LESS THAN [Ra02]		GREATER THAN [Le15]	
Setpoint																	
Actual																	
TREND (Circle One)		SG1		SG2		SG3		SG4		H ₂ Concentration		BETWEEN [Pr13] and [Pr07]		LESS THAN [Ra02]		GREATER THAN [Le15]	
		↑ STABLE		↑ STABLE		↑ STABLE		↑ STABLE		%		↑ STABLE		↑ STABLE		↑ STABLE	
		↓ STABLE		↓ STABLE		↓ STABLE		↓ STABLE		%		↓ STABLE		↓ STABLE		↓ STABLE	
		↔ STABLE		↔ STABLE		↔ STABLE		↔ STABLE		%		↔ STABLE		↔ STABLE		↔ STABLE	
Indicated Value:		%		%		%		%		%		%		%		%	
Correction Factor:		%		%		%		%		%		%		%		%	
Adjusted Value:		%		%		%		%		%		%		%		%	

As part of each debrief, additional feedback related to the new SAMG format and structure were gathered. Some of the key areas of feedback are provided below:

- All participants have noted an enhanced confidence with the product, believing in its strategies and its improved ease of use because it is now written to look more like a procedure.
 - Participants with little to no background preparation in the new SAMG or SAMG in general were able to become comfortable with the product within the first tabletop scenario, proving the improved usability of the product.
- The new SAMG is a marked improvement from the previous versions.
 - The structure and flow is a substantial improvement from the previous versions.
 - The Diagnostic Process Guideline (DPG) is a well-designed focal point or ‘home base’ that promotes easier assimilation of plant data and allows that data to be seamlessly processed so that priorities can be set with minimal analysis required.
 - The DPG removes ‘analysis paralysis’ frequently experienced with users of previous SAMG.
 - The DPG has beneficial prioritisation that its users feel will positively help improve the ability to diagnose plant conditions and stabilise a severe accident.
- The guidance is more usable; it is symptom focused and requires less analysis time from the users.
- It was noted at every host plant that all users perceived that the new SAMG was easier to formulate a successful strategy to deal with the plant conditions at hand, no matter what conditions presented themselves during the tabletop exercises.
- The “left hand page” information (see Section 4.3.2, bullet 3 under “Action Based TSC Guidance”) is extremely useful and allows users to instantly have a better understanding of why an action should be performed.

4.3.4 Future SAMG maintenance

Following the issuance of the final PWROG SAMG Revision 0 (January 2016) the PWROG has committed to maintaining the SAMGs going forward similar to the vendor specific EOPs. An SAMG maintenance programme is currently being developed that will implement a formal process for receiving SAMG feedback, evaluating if it warrants a change to the generic SAMG, implementing changes to the generic SAMG and rolling out revisions to the PWROG SAMG. This programme has been committed to by the PWROG and implementation of the most recent revision to the PWROG SAMGs will be part of the NRC Reactor Oversight Process (ROP) inspection programme.

4.4 BWR generic SAMG update by BWROG

4.4.1 Background

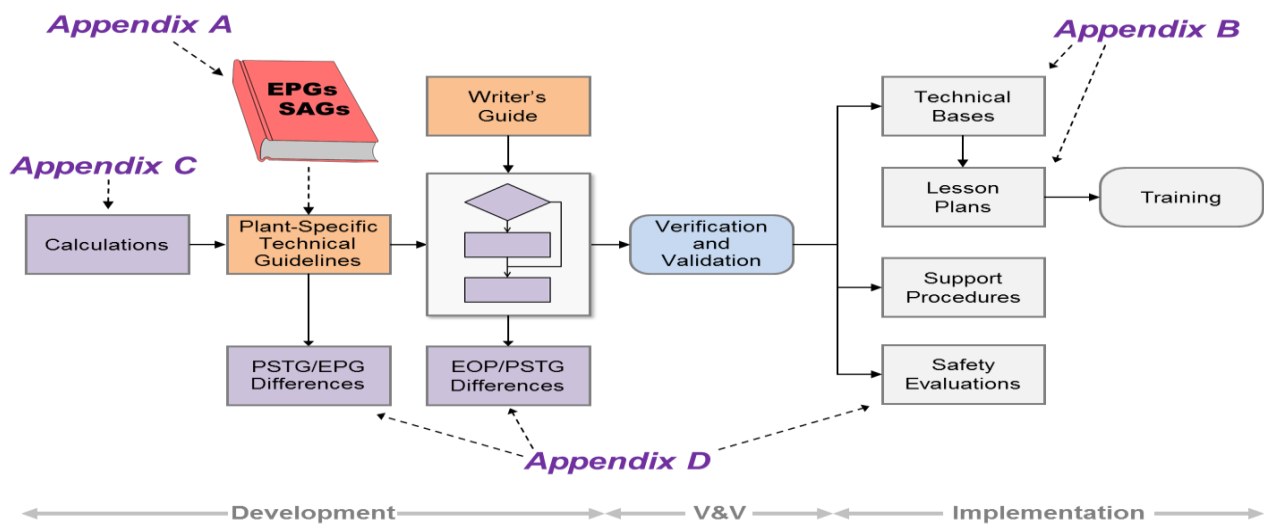
The BWROG sustains a generic committee (i.e. Emergency Procedure Committee [EPC]) which maintains the Emergency Procedure and Severe Accident Guides (EPGs/SAGs) for its membership. The committee membership includes Japan, Mexico, Spain, Switzerland, Taiwan and the US.

The BWROG EPC provides generic procedure guidance that is modified by the operating utility to be plant specific. The generic guidance is developed from the operational insights of the individual plants. The committee meets four times per year to assess the guidelines, identify issues and resolve areas of concern. Figure 2 provides a summary of the overall process used by the BWROG to improve and maintain the EPG/SAGs.

The BWROG EPGs/SAGs are symptom-based flowcharts, as used by operations, and provide guidance when the plant is not responding appropriately to scenario-based guidance (e.g. abnormal operating procedures [AOPs], etc.). The EPG/SAGs are supported by TSGs that include calculational aids to assist in interpreting instrumentation response. Currently, there are more than 20 calculational aids available for use by the technical support centre.

Accident phenomena, the performance of plant systems and regulatory compliance form the basis for the EPGs/SAGs. The symptom-based guidance uses any available system margin (established by design and regulation) to prevent core damage or mitigate an accident (through defeat of system interlocks and system protection logic, etc.). Prevention of core damage has the highest priority if a decision is to be made concerning the use of plant systems/equipment. A significant amount of effort is undertaken by the EPC to ensure that the EPGs/SAGs are not written for specific scenarios, but based on maintaining a set of controlling parameters within an acceptable operating band using available equipment and instrumentation. The acceptable operating band can be based on plant-specific design features, based on compliance to regulations or based on known plant system performance. To assist operations when using the EPGs/SAGs, various analytical tools and the TSGs are available to help with forecasting the time to when certain conditions are expected.

Figure 2: BWROG Process – Generic to Plant-Specific EPG/SAGs



4.4.2 Verification and validation

Verification and validation (V&V) are an integral part of the BWROG's generic and plant-specific EPG/SAG developmental process as shown in Figure 2. V&V includes analytical simulation and feedback from the plant-specific groups that implement (including feedback from operator training) the generic guidance.

The EPC membership includes participants with backgrounds in plant operations, engineering, accident phenomenology, regulation, training and procedure development. Insights from these various groups are used to verify and validate the generic guidance. The committee develops, verifies and validates guidance based on input from these backgrounds; the generic guidance is used to develop plant-specific guidance based on specific design features and regulations.

Probabilistic safety assessment (PSA) (specific scenarios) and analytical results provide results that are useful for V&V activities for the EPGs/SAGs. V&V are an embedded feature of the BWROG's maintenance of the EPGs/SAGs with feedback loops to ensure the identification of both generic and plant-specific issues associated with the EPGs/SAGs. Insights from PSA and analytical results are scenario dependent and are useful for developing AOPs, but the results cannot be the only bases for the development of symptom-based guidance. Scenario specific results are used in the verification of the SAGs with validation being performed during implementation and feedback from the operator training programmes.

The EPC members closely monitor activities in regulation, insights obtained from operation and engineering, training programmes, and ongoing programmes designed to better understand accident phenomenology in the continual quest to improve the EPGs/SAGs. These technology monitoring activities are used to assess the generic guidance and the committee makes recommendations for improvements through an issue resolution process. Once an issue is identified and accepted by the committee, the following issue resolution categories are used by the EPC for its disposition:

- **APPROVED** – consensus on a change to the EPGs/SAGs; implementation of approved changes is the responsibility of member utilities with due consideration given to applicability to their plant, safety significance and improvement in operator response to plant emergencies.
- **ACCEPTED** – consensus agreement on an interpretation of the existing guidelines; as a result of this interpretation, it is concluded that changes to the EPGs/SAGs are not required.
- **CLOSED** – consensus resolution cannot be reached and it is subsequently determined by the EPC or Prime Representatives that resources should no longer be applied towards issue resolution.
- **WITHDRAWN** – is used for issues which for some reason have subsequently been determined to not meet the screening criteria or are addressed by another issue.

EPC accepted issues require 100% consensus to make an approved change to the guidelines. Issues are also provided a priority level by the BWROG. High priority items are addressed as soon as possible and issued to the fleet for implementation, while editorial or lower levels issues are updated during major updates to the generic guidance. Executive oversight of the recommendations is used to foster incorporation of the updates into the fleet of plants. Going forward in the US, the NRC's Reactor Oversight Process will be part of the fleet wide process to improve and foster timely implementation of the BWROG's generic SAG guidance. It is typically expected that major updates to the EPGs/SAGs be incorporated within two refuelling outages or three years as appropriate.

4.4.3 Future SAG maintenance

The BWROG has committed to maintaining and improving the SAGs in accordance with its membership recommendations and members' regulatory requirements. This includes developing integrated procedure guidance for the non-power operating modes. In regard to improving and maintaining the generic guidance, the BWROG EPC is also working with the U.S. NRC Reactor Oversight Process inspection programme, the Institute of Nuclear Power Operations, the U.S. Department of Energy, the PWROG, the IAEA and EPRI to foster continual improvement and implementation of the guidance in the BWR fleet. Items identified by these organisations are addressed by the EPC on a case-by-case basis through an EPC subcommittee. One TSG type improvement example that the committee is working on (2016) is the development of an improved calculational aid with the U.S. Department of Energy for estimating water level and leak rates using point and click type technology (iPhone, iPad Android type tool with communications).

4.5 Summary

All countries participating in this project have installed SAMG. Most commonly implemented are adaptations of the strategies based on WOG SAMG for plant-specific conditions. Finland and Sweden have SAMG developed by the utilities, which date from around 1990 and originate from the installation of severe accident mitigation systems at that time. Except for the US, where SAMG is a voluntary industry initiative, SAMG is today a regulatory requirement. The status of SAMG implementation varies from fully implemented SAMG, which are validated and verified, to just recently implemented SAMG with ongoing plant-specific adaptations. The regulatory review of the design and implementation of SAMG varies from country to country. There have been several methods used for the verification and validation of SAM, of which the most important are summarised in Section 3.5.

Regarding effectiveness criteria of SAMG, most participants in the questionnaire mention the common objectives of maintaining containment integrity and limiting radioactive releases; in Finland, staying within a limit of 100 TBq of Cs-137 is to be demonstrated. Specific approaches to evaluate SAMG effectiveness, mentioned by different countries, are (among others):

- approaches using severe accident codes to simulate a larger number of scenarios – base case and variations – to evaluate the impact of SAMG actions;
- demonstration of the operability of systems supporting main goals, e.g. filtered venting for maintaining containment integrity and limiting radioactive releases;
- the German response is a reminder of the need to: i) use appropriate analysis tools; ii) demonstrate and document the feasibility of each SAMG action.

Important examples of suggestions for further activities to assess SAM effectiveness are the continued development of full-scope severe accident simulators, in spite of their existing limitations, and the exchange of experience both among developers and users. Another initiative for further activities is the extension of EOP analyses to SAMG.

5. Guidance for informing severe accident management guidance and actions through analytical simulation

5.1 Introduction

Analytical simulations described in this report are the simulations of severe accident progression and consequences using severe accident analysis computer codes. Simulations are performed with and without crediting operators' actions in order to gain the understanding of the severe accident management guidance (SAMG) specified mitigation actions and their associated temporal and environmental constraints, and to assess their feasibility under plausible accident conditions. With this regard, the overall objective of performing such analytical simulations is to provide necessary detailed information used to inform and assess the feasibility and efficiency of SAMG-specified actions under severe accident conditions.

The results of expensive multi-year severe accident research programmes to date are used to improve our understanding of severe accident phenomena and capability of modelling those phenomena. Using the state-of-the-art severe accident analysis codes for simulating severe accident progression and consequences with and without operators' actions allows utilisation of the current knowledge and research data in the optimisation of severe accident management (SAM) actions. In this regard, analytical simulation is a state-of-the-art approach.

However, it must be realised that applications of this approach to severe accidents still have significant uncertainties. Assessing SAM action through analytical simulation should take into account those uncertainties. For this reason, the emphasis of this report is to recommend providing insights into the action under examination with a manageable number of numerical simulations, rather than collecting a large volume of computer code outputs and using them to directly compare with the so-called "success" criteria without a full understanding of the physics behind and the limitations inherited.

The specific objectives of SAM action assessment are given in Section 3.3. The focusing areas of concerns pertinent to informing SAM actions through analytical simulation are described in Section 3.4. The purpose of this section is to provide further pragmatic guidance on analytical simulation of SAM actions in order to achieve the stated objectives. This section starts with a description of roles of computer codes used to support SAM (Section 5.2), then a discussion on the general methodologies suitable for SAM action assessment (Section 5.3), documentation of the simulation results (Section 5.4), interpretation and use of the simulation results to inform SAM actions (Section 5.5). Finally, examples of using analytical simulation to inform SAM actions are provided in Appendix C.

5.2 Roles of computer codes used to support SAM

This subsection discusses severe accident analysis computer codes and their use to assess SAM measures. The first part of this subsection provides an overview of SAM measures and general approaches to assess those measures (Section 5.2.1), and a high-level discussion on the use of severe accident analysis codes to support SAM activities (Section 5.2.2). The second part gives a summary of established severe accident analysis codes, including codes used to complement and support severe

accident analyses and a few three-dimensional code systems for the analysis of dedicated severe accident phenomena (Section 5.2.3 and Appendix B in detail).

5.2.1 Overview of SAM measures

For the assessment of SAM measures, deterministic computer code systems for event analyses play an important role. One of the main applications of severe accident analyses is the assessment of the effectiveness of SAM measures realised in NPPs. These SAM measures are mitigative measures installed in the plant as parts of SAMG and required to be implemented only if the measures specified in emergency operating procedures (EOPs) were unable to prevent severe fuel damage. All the measures might be in connection with specific hardware implemented in the plant for severe accident conditions or with the use of non-dedicated systems used in the design basis area.

Examples of preventive measures that may be called in EOPs are primary and secondary side bleed and feed for pressurised water reactors (PWRs), diverse depressurisation of reactor pressure vessel (RPV) for boiling water reactors (BWRs), and use of mobile diesel generators and mobile pumps for both PWRs and BWRs. Mitigative severe accident management guidelines (SAMGs) may call, for example, for passive autocatalytic recombiners (PARs; PWRs and BWRs), filtered containment venting systems (PWRs and BWRs), N₂ inertisation of drywell and/or wetwell (BWRs). The assessment of this kind of preventive and mitigative measures by deterministic event analysis codes has already been a common practice.

The focus of this report is on the assessment of mitigative measures pre-determined and documented in the plant-specific SAMG, rather than the preventive EOP measures. Typical mitigative measures called by SAMG include:

For PWRs or BWRs	For PHWRs (e.g. CANDU Reactors)
<ul style="list-style-type: none"> • Recovery activities of failed systems and components • Additional injection of water into RPV, reactor cavity, and/or containment (by mobile pumps and reservoirs, by using operational systems, by water injection from spent fuel pool using existing systems to connect, etc.) • External RPV cooling • Increased heat removal from containment atmosphere (e.g. operation of heat exchanger of the ventilation system) • Minimising release of radionuclides into the environment (e. g. optimised operation of unfiltered and filtered ventilation systems) • Reduce containment hydrogen (e.g. PARs) 	<ul style="list-style-type: none"> • Inject water into the heat transport system • Control moderator conditions (adding water to the calandria vessel or restoring moderator cooling) • Control calandria vault conditions (adding water to the calandria vault or restoring end shield cooling) • Reduce fission product releases (e.g. closing containment isolation/control valves, plugging penetrations, etc.) • Reduce containment conditions (e.g. reducing containment pressure using air coolers) • Reduce containment hydrogen (e.g. using igniters, PARs, and filtered air discharge system)

For most of the cases the modelling of those SAM measures can be traced back to the modelling of mass and energy sources/sinks and control functions, which should be manageable by the code systems discussed below.

Codes usually applied in the assessment of SAM measures can be either integral or detailed severe accident analysis codes. However, for the assessment of preventive accident management measures, which are restricted to situations before core damage, detailed thermal-hydraulics codes like ATHLET, CATHARE, and RELAP5 could be applied as well, since the plant is still in its original configuration especially as the core is not yet molten. These thermal-hydraulics codes are used routinely for the analysis of anticipated operational occurrences and design basis accidents, but their application range typically covers beyond-design-basis accident scenarios with intact core geometry or limited core

degradation as well. As this report focuses on assessments of only mitigative SAM measures by computer simulation, it does not describe the thermal-hydraulics codes mentioned.

5.2.2 *Use of severe accident computer codes*

IAEA Safety Reports Series No. 56 [22] contains descriptions of general use of severe accident analysis computer codes and application of severe accident analyses. This subsection is intended to complement and update the information and guidance published in [22].

In particular, the current practices with respect to the use of severe accident analysis computer codes to support various activities related to the development, implementation and evaluation of a SAM programme in an NPP are summarised here. The intent is to provide an overview regarding the use of severe accident computer codes in the domain of SAM and thus an improved understanding of the role of such an analytical approach. With this intention, the summary below is limited to a description of the purposes of severe accident analyses or assessments.

From the current practices, severe accident analysis computer codes have been used to support various types of analyses and assessments, including:

- support of Level 2 and Level 3 probabilistic safety assessments (PSA);
- confirmation of SAM strategies;
- supporting analyses for special topics such as in-vessel retention (IVR) of core debris;
- analyses in support of SAM such as equipment/instrument survivability assessment;
- analyses to understand SAMG-specified actions and inform SAM effectiveness (the topic of this report).

Support of Level 2 and Level 3 PSA

Severe accident analyses play an important role in performing Level 2 and Level 3 PSA. For example, a main objective of Level 2 PSA support analysis using severe accident computer codes is to perform integrated plant response simulations of given representative severe accident scenarios so that the safety goals (e.g. determination of severe core damage frequencies and frequencies of release categories) can be quantitatively evaluated. More specifically, this type of severe accident analyses looks into:

- radioactive release source terms for Level 2 and Level 3 PSA to assist in demonstrating that the plant meets the established safety goals and quantitative health objectives (in terms of individual early fatality and latent cancer fatality risk);
- timing and duration of significant stages of the accident under analysis to assist in demonstrating that the plant provisions, including complementary severe accident features, available mitigating measures, and procedural considerations, are effective to place a severe accident in a controlled and stable state;
- determination that the global safety concept of the plant under examination is well balanced;
- input for assistance, when needed, to establish and validate the severe accident mitigation measures, emergency measures and management guidelines.

Confirmation of SAM strategies

This type of severe accident analysis involves simulations of severe accident progression in an NPP, with the aim at confirming the technical basis and SAM strategies identified to support the development and implementation of SAMG for the NPP. The analysis provides:

- link to the SAMG technical information on severe accident progression and related phenomena;
- background material on severe accident phenomena for training of the SAMG users;
- background information to support the rationale for the development of the key elements of SAMG;
- technical justification and details for the development of computational aids as part of SAMG.

Similar analysis to confirm candidate high-level actions (CHLAs) during the development of generic SAMG for PWR/BWR reactors was documented in the EPRI report: “Severe Accident Management Guidance Technical Basis Report, Volume 2: The Physics of Accident Progression” [19].

Support of addressing special topics related to SAM

This type of analysis involves simulations of severe accident progression and consequences for the purpose of addressing special topics such as in-vessel core debris retention, ex-vessel core debris cooling and mitigation, containment integrity and associated challenges (e.g. selection of a containment venting option for installation), hydrogen production, distribution and mitigation in containment, etc. This type of analysis, in conjunction with known severe accident phenomenology and relevant experimental data, either directly helps develop a resolution to an SAM issue or provides quantitative information such as heat load, temperature, pressure, etc. for further detailed assessments to deal with the issue. For such cases, in addition to the use of a severe accident analysis computer code, more mechanistic code systems are often used to provide more detailed modelling of a single severe accident phenomenon or a subset of the phenomena.

Examples of this type of supporting analyses are:

- demonstration of in-vessel retention (IVR) using the MAAP4-CANDU computer code for accident conditions and calandria vessel temperature profiles, and ANSYS for structural and stress analyses of the vessel (Canada);
- implementation of the external vessel retention (EVR) based on complicated simulations by the MC3D computer code (France);
- implementation of the wet cavity strategy based on a series of code simulations such as the DECOSIM computer code (Sweden);
- allocation of passive autocatalytic recombiners (PARs) based on the COCOSYS and GASFLOW simulations (Germany);
- development of technical basis for containment protection and release reduction based on MELCOR simulation of various mitigation alternatives (USA).

Assessments of equipment and instrument survivability and facilities habitability to support SAM

A typical example of SAM supporting analysis using severe accident computer codes is to provide environmental conditions (e.g. temperature, pressure, steam content, and radiation dose) to assess whether the equipment and instruments required during the execution of SAMG would survive in a severe accident and function when they are called upon.

Similarly, those predicted environmental conditions around the facilities (e.g. main control room, secondary control area, emergency response centre, etc.) required for SAM are used to assess whether these facilities are habitable for SAM personnel in a severe accident. As part of SAM support analysis, harsh conditions and the key pathways that field operators will take to implement SAMG-specified

actions are also estimated and used to assess if those pathways are accessible or determine what personnel protection hardware is required.

Informing SAMG

Severe accident simulations are performed with and without crediting SAMG-specified actions with the aim of understanding the positive and negative effects of the actions and providing necessary detailed information used to assess the effectiveness of those actions under severe accident conditions. This type of analytical approach as one of the means to validate SAMG is the main topic of this report. The general guidance on use of this approach is provided in this report.

5.2.3 Severe accident analysis computer codes

IAEA Safety Report Series (SRS) No. 56 [22], published in 2008, contains a section on the use of computer codes for the analysis of severe accidents. It groups the severe accident computer codes into three categories: fast-running integral codes, detailed codes and special (dedicated) codes. It also presents requirements for modelling severe accident phenomena, and discusses the verification and validation of the severe accident computer codes, and user qualification and user effect on accident analysis. Annex I of SRS No. 56 [22] presents main features of selected severe accident codes.

This subsection of the WGAMA report, together with Appendix B, is to complement and update the information published in the IAEA SRS No. 56 [22] with a focus on descriptions of main features of severe accident computer codes or code systems used to date.

It should be pointed out that it is necessary to conduct this type of update on a regular basis in the future to reflect on the ongoing developments relating to these codes and methods.

5.2.3.1 Overview

In this report, severe accident analysis computer codes are described in the following four groups:

- Integral codes
- Detailed codes
- Complementary codes
- Dedicated multi-dimensional (e.g. 3-D) code systems

Severe accident analysis computer codes used to assess SAM measures can be either integral codes or detailed codes, or a combination of both. A distinction is made here between so-called integral codes (generally based on parametric models, but now moving towards more mechanistic models) and detailed codes largely based on mechanistic modelling. In addition, codes not specifically developed for severe accident analysis like computational fluid dynamics (CFD) codes and structural mechanics codes are applied in order to assess single effects or a subset of phenomena and physical processes encountered in a severe accident.

Integral codes are based on a combination of phenomenological and parametric models for all relevant phenomena of a severe accident including the release and transport of radionuclides important for the calculation of the source term to the environment. They are able to model both the in-vessel and the ex-vessel progression of severe accident sequences by modelling the reactor circuit and the containment behaviour within one simulation. These integral codes may employ a lumped parameter approach for certain or all components being modelled to simplify the mathematical representation of spatially distributed physical systems and to facilitate the use of empirical or semi-empirical models that describe the behaviour of the systems. Originally, these integral codes were typically designed to be rather fast running to allow the whole severe accident simulation starting from the initiating event up to the end of the release of radionuclides into the

environment. Furthermore, they should make it possible to run a large number of different scenarios with limited time effort, e.g. in support of PSA level 2 studies.

Detailed codes aim at a best-estimate modelling of phenomena or set of phenomena and typically involve the numerical solution of integral-differential equations. For some applications, they may still employ a lumped parameter approach. Among other purposes, they serve as benchmarks for integral codes. Their computation times are generally higher and they are developed to simulate only some parts of the plant because of the complexity of the phenomena to be simulated. Often, they are limited either to specific accident phases such as the in-vessel or the ex-vessel phase of severe accident scenarios or to different application purposes like the analysis of the behaviour inside the reactor circuit or the containment. The recent code development shows, however, that coupled versions of detailed codes are increasingly used for the whole simulation of severe accident scenarios in both the reactor circuit and the containment and for both accident phases. For example, the combination of ATHLET-CD (for the behaviour of the reactor coolant system and core degradation) and COCOSYS (for the containment behaviour and molten core-concrete interaction), both developed by GRS, has been successfully applied for the analysis of severe accidents.

The ongoing code development for the integral codes and the increasing demand for more realistic simulations have led to more complex and detailed modelling. Furthermore, the performance of computer hardware has been steadily increasing thus reducing the computational times for severe accident analyses proportionally. For these reasons, the application of detailed coupled codes like ATHLET-CD/COCOSYS for severe accident analyses has become a serious option.

Complementary computer codes that are often coupled with codes for deterministic accident analysis are used to assess the manual actions of EOP and SAMG measures in more detail or to perform sensitivity and uncertainty analyses, which are important for sequences with a high degree of manual actions.

Finally, **dedicated multi-dimensional (e.g. 3-D) code systems** are also used in the field of severe accident analyses which are dedicated to the simulation of a single phenomenon or a subset of physical processes encountered in a severe accident. These include, for example, CFD codes for the solution of Navier-Stokes thermal-hydraulics equations in three-dimensional (3D) geometry as well as 3D structural mechanics codes for the calculation of the behaviour of solid structures under severe accident conditions, like the containment itself.

The severe accident analysis computer codes that are typically used for the assessment of SAM measures are briefly described below. More detailed descriptions of the current toolsets used in the assessment of SAM measures are provided in Appendix B.

5.2.3.2 Integral codes

MELCOR

The MELCOR code is being developed by Sandia National Laboratories (SNL) under the sponsorship of the U.S. Nuclear Regulatory Commission (NRC). The latest version released is 2.1. It is a fully-integrated code for the simulation of the progression of severe accidents not only in light water reactors (LWRs), but also in non-LWRs as well as other facilities (e.g. spent fuel pool, dry cask storage, etc.). It was originally designed as a fast-running PSA severe accident analysis code using simplified parametric models but

meanwhile – due to further development and significant advances in computing power – serves as a best-estimate code for predicting the response of a plant to a severe accident. MELCOR is a modular code which consists of three general types of packages: basic physical phenomena, reactor-specific phenomena and support functions. These packages model the major systems of a nuclear power plant and their associated interactions. Thermal-hydraulics, core melting, the release of fission products and transport processes are treated by dedicated models. For a number of other phenomena, existing codes have been integrated into the MELCOR architecture.

The MELCOR code is intended to predict accident progression from the initiating event, to the point of core uncovering, through vessel failure and the relocation of core debris into the containment, to the point of containment failure and the prolonged escape of radioactive materials into the nuclear power plant environment. The code provides input to a companion code, MELCOR Accident Consequence Code System (MACCS), for the analysis of radioactive material dispersion in the environment and the consequences of this dispersion. The MELCOR code has a substantial, worldwide community of users. The code has a rather flexible architecture so that it can be used to predict accident progression in many different types of nuclear reactors, like PWR, BWR, water-water energetic reactor (VVER), high power channel-type reactor (RBMK) and high temperature gas-cooled reactor (HTGR).

ASTEC

ASTEC (Accident Source Term Evaluation Code) has been jointly developed by the French Institut de Radioprotection et de Sûreté Nucléaire (IRSN) and the German Gesellschaft für Anlagen- und Reaktorsicherheit (GRS). The code is intended for the simulation of the behaviour of whole nuclear power plants under severe accident conditions taking into account severe accident management by procedures and engineering systems, from the initiating event until an eventual radiological release into the environment.

As of this writing, the most recent version of ASTEC is 2.0 rev. 3. ASTEC consists of a set of modules over which an overview is given by Figure B-1 in Appendix B. Each of the modules simulates a zone of the plant or a set of physical phenomena. Of the latter, except for steam explosions and the mechanical response of the containment, most of those relevant in severe accidents are modelled.

Currently, ASTEC can be applied to different types of PWR and VVER nuclear power plants. However, there is ongoing work for the adaptation of ASTEC models to BWR and CANada Deuterium Uranium (CANDU) type reactors. In this context, the focus is on the modelling of core degradation whereas most other models have already been shown to be applicable.

MAAP

The Modular Accident Analysis Program (MAAP) was originally developed for the Industry Degraded Core Rulemaking (IDCOR) programme in the early 1980s by Fauske & Associates, LLC (FAI). At the completion of IDCOR, ownership of MAAP was transferred to the Electric Power Research Institute (EPRI), which maintains and licences the code to user organisations worldwide. FAI maintains its role as the developer of MAAP, focusing on model and code improvements and release of updated versions. Starting in the late 1980s, the MAAP3B version became widely used, first in the United States and then worldwide, to support success criteria determination, human action timing evaluations and Level 2 analyses for individual plant examinations (IPEs).

MAAP4 (i.e. version 4 of the code), released in mid-1990s, is a fast-running integral code which simulates the response of LWR power plants during severe accidents. The code is used to do the following:

- predict the timing of key events (for example, core uncovering, core damage, core relocation to the lower plenum and vessel failure);
- evaluate the influence of mitigative systems, including the impact of the timing of their operation;
- evaluate the effects of operator actions;
- predict the magnitude and timing of fission product releases;
- investigate uncertainties in severe accident phenomena.

MAAP4 models the following severe accident phenomena:

- cladding oxidation and hydrogen evolution;
- core material eutectic formation;
- core relocation;
- lower head–core debris dynamics;
- failure of vessel penetrations and/or the lower head;
- debris entrainment;
- debris-concrete interactions;
- ignition of combustible gases;
- pH and iodine chemistry in containment;
- fission product release, transport and deposition;

The code calculates the condition of nuclear power plants during severe accidents taking into account the core, the reactor vessel, and the containment and tracking the transport of energy and mass considering the inventories of water, hydrogen, aerosols and radioactive species. It is applied for the analysis of severe accident progression scenarios both for the reactor core and the spent fuel pool.

Parallel versions of MAAP4 support boiling water reactors (BWRs) and pressurised water reactors (PWRs), and there are also unique versions for CANDU, VVER and advanced test reactor (ATR) designs. The PWR and BWR versions contain the same core model, containment and reactor/auxiliary building model, fission product model, and input and output schemes. They have distinct primary system models and engineered safeguards models.

MAAPv5.00 was released in 2008, and additional modifications were included in MAAPv5.01, which was distributed in 2011. Further enhancements were introduced in MAAPv5.02. At the time of writing, the most recent (non-beta) version of MAAP offered is the 5.02 version (December 2013).

MAAP4 PWR

The PWR primary system model calculates the thermal-hydraulic conditions in the reactor pressure vessel, the hot legs, the cold legs, and the primary side of the steam generators. The pressuriser is modelled as a single control volume, with one water pool and one gas node. The thermal-hydraulic model calculates water transport, gas transport, steaming, and heat transfer to the structures that interface with the secondary side and the containment. In addition to condensation onto the inside surfaces of the steam generator tubes, steam can condense on cold emergency core cooling system (ECCS) water injected into the primary system. When the accident progresses to core uncovering, the level of detail in the calculations increases, and the modelling includes such phenomena as natural circulation of superheated gases in the vessel and in the hot leg (countercurrent flow). The thermal-hydraulic model does not

explicitly account for the conservation of momentum, which requires a substantially more complex model.

MAAP4 BWR

The BWR primary system model calculates the thermal-hydraulic conditions in the reactor pressure vessel. It tracks the mass and energy of water pools in the downcomer (including the water inside jet pumps and in the recirculation loops), in the core (including the water above the active core extending into the standpipes, separators and upper plenum), in the control rod drive tubes, and in the lower plenum. The remaining free volume constitutes a single gas space. The gas pressure is imposed on the water pools, and the individual water masses and energies are then used to determine the temperature of each pool. MAAP4 also tracks the two-phase mixture volume in each water region. The gas space is divided into eight nodes for heat transfer and gas flow calculations. The code tracks the gas temperature, mass fraction of hydrogen and fission product masses in each of the gas nodes. Eleven primary system heat sinks are modelled, each as a two-dimensional slab.

MAAP4 VVER

MAAP4/VVER is a computer code for the simulation of severe accidents and accident management at VVER 440/230, 440/213, and 1000 power reactors. It considers thermal-hydraulic and fission product phenomena in the primary system, confinement or containment regions, and auxiliary reactor building rooms, and has a user interface for easy simulation of operating procedures and emergency actions. MAAP4/VVER is based on the standard MAAP4 code and it incorporates revisions to consider horizontal steam generators, movable control and fuel assemblies, and other unique VVER features.

MAAP5-VVER is currently under development with the objective to simulate advanced VVER designs.

MAAP4-CANDU

MAAP4-CANDU contains the CANDU specific models including the core and calandria vessel, shield cooling system, reactor vault, pressure and inventory control, and engineered safeguards (e.g. containment cooling sprays, emergency core cooling, etc.). Within these larger groups there are models such as the calandria vessel debris bed behaviour (heat transfer, melting, crust formation, interaction with the calandria vessel) and the response of the calandria vessel to a large core debris heat source.

One of the most important distinguishing features, between MAAP4-CANDU and other MAAP4 versions, is the CANDU reactor core with fuel bundles situated inside horizontal pressure tubes and calandria tubes. In addition, the large quantities of relatively cool water (moderator and calandria vault) provide significant heat sinks, distinguishing the CANDU models from LWR models.

The MAAP4 CANDU Channels System models a broad spectrum of physical processes in the core that might occur during a severe core damage accident, such as:

- fuel and fuel channel temperature excursions, deformation of fuel and fuel channels, and interactions with the moderator system;
- zirconium steam reaction;
- thermal mechanical failures of fuel channels;
- disassembly of fuel channels;
- formation of suspended debris beds;
- motion of solid and molten debris beds;

- interaction of the core debris with steam; and
- fission product release, transport and deposition.

In particular, the Channels System models the CANDU feeders, end fittings, fuel channels and fuel. The models contained in the Channels System concentrate on the behaviour of these core components within the calandria vessel as the fuel channels disassemble, form suspended debris supported by intact channels, and collapse or melt to the terminal debris bed within the calandria vessel. The Channels System models characteristic fuel channels and their contents once the channels are dry on the inside, during channel heating and subsequent processes (e.g. zirconium steam reaction, channel disassembly, and debris behaviour). Each characteristic channel represents a larger number of associated channels with similar powers, elevations and feeder geometries.

ECART

ECART (ENEL Code for the Analysis of Radionuclide Transport) is an integrated primary circuit and containment code, for nuclear power plant severe accident analysis, but it can be also applied to fusion reactors, industrial plants, etc.

The work on ECART started in 1989, and utilities ENEL and EDF contributed to its initial development. ECART is presently developed by ERSE (Milan, Italy). A more detailed description of the code is given in Appendix B.

THALES-2

The THALES-2 code is an integrated severe accident analysis code developed at the Japan Atomic Energy Agency (JAEA), formerly JAERI (Japan Atomic Energy Research Institute) to simulate the accident progression and transport of radioactive materials for the PSA of nuclear power plants. In 1982, JAERI developed, as a first step, the computer code system THALES (thermal-hydraulic analysis of loss-of-coolant emergency core cooling and severe core damage) for the analysis of accident progression. In 1988, the code was combined with the ART (Analysis of Radionuclide Transport) code developed also by JAEA and the THALES/ART code system started. After that, the code system was improved by coupling the radionuclide transport models with the thermal-hydraulic ones and a prototype of single code, namely, the THALES-2 code was completed in 1991. Then, the abbreviation THALES was changed to the Thermal-Hydraulics and radionuclide behaviour Analysis of Light water reactor to Estimate Source terms under severe accident conditions.

5.2.3.3 Detailed codes

ATHLET-CD

The ATHLET-CD code is being developed and validated by GRS for accidents resulting in core damage. The code system is based on the thermal-hydraulics code ATHLET (Analysis of THERmal-hydraulics of LEaks and Transients) and the Core Degradation (CD) part. The thermal-hydraulic system code ATHLET is also being developed by GRS for the analysis of the whole spectrum of anticipated operational occurrences and design basis accidents (leaks and transients) in PWRs and BWRs. It can be applied also to beyond-design-basis accidents without core damage and has been expanded to additional reactor types like VVER and RBMK. The main code features are advanced thermal-hydraulics, modular code architecture, separation between physical models and numerical methods, pre- and post-processing tools and portability to the prevalent computer platforms. ATHLET has been expanded to the simulation of core melt scenarios by coupling with the CD part. The development and integration of the CD part is being done in close co-operation with the “Institut für Kernenergetik und Energiesysteme (IKE)”, of the University of Stuttgart. By integrating the models for the formation and movement of metallic and

ceramic melts in the core area and the thermal behaviour of particle beds, as well as for the release of fission products and aerosols in the core area and their transport and deposition in the cooling circuit, the application range of the computer code has been extended significantly. This has been demonstrated by successful post-test calculations of bundle and integral experiments, such as CORA, QUENCH, LOFT-LP-FP2 and Phébus FP, or the TMI-2 accident and the incident at Paks-2 (NEA 2008). As demonstrated by several applications of the code, full plant simulations can be performed by coupling ATHLET-CD with COCOSYS. Appendix B provides more detailed descriptions of the code.

COCOSYS

COCOSYS is being developed and validated at GRS for the comprehensive simulation of severe accident propagation in containments of light water reactors. The code allows the simulation of all relevant phenomena, containment systems and conditions during the course of design basis accidents and severe accidents. In COCOSYS, mechanistic models are used as far as possible for analysing the physical and chemical processes in containments. Essential interactions between the individual processes (e.g. between thermal-hydraulics, hydrogen combustion as well as fission product and aerosol behaviour) are treated in a comprehensive way. With such a detailed approach, COCOSYS is not restricted to relevant severe accident phenomena, but is also able to demonstrate interactions between these phenomena as well as the overall behaviour of the containment. Appendix B provides more detailed descriptions of the code.

GOTHIC

GOTHIC (Generation of Thermal-Hydraulic Information for Containments) is an integrated, general purpose thermal-hydraulics software package for design, licensing, safety and operating analysis of nuclear power plant containments, confinement buildings and system components. The code was developed by NAI (Numerical Applications, Inc.). There is ongoing development and maintenance support by the EPRI GOTHIC Enhancement Project (since 1993).

GOTHIC has been evolved from COBRA-NC, a simulation code that solves the multicomponent, compressible, three-dimensional, two-fluid, three-field equations for two-phase flow. The code has been extended for multiphase flow field of vapour, liquid, droplets, mist and ice. Enhancement of component models has been implemented in hydrogen burn, fan coolers, radioactive isotopes, radiation heat transfer, an advanced wall condensation (diffusion layer model) model, passive autocatalytic recombiners (PARs), igniters, etc. As a CFD code, the code has been implemented with the standard k-e model, efficient matrix solvers (Gauss-Siedel, conjugate gradient and multigrid), and a porous body model.

The package is composed of GOTHIC_P (Pre/Post processor), GOTHIC_S (Solver) and GOTHIC_G (Graphics). A capability of the shared memory parallel processing enables handling relatively large size problems with monitoring with a graphical user interface (GUI).

GOTHIC code is a three-dimensional (3D) code. However users can select “single volume” components using the code as a lumped parameters code.

In this report, GOTHIC is categorised as a detailed code because the code has been widely applied to detailed containment integrity analyses with a combination of lumped parameter nodes and relatively coarse distributed meshes. For applications as a CFD code, several open literatures can be found for those subjects such as helium mixing tests and safety analyses of the advanced reactors. Appendix B provides those references and more detailed descriptions of the code.

SAMPSON

The SAMPSON code has been developed in the IMPACT project in Japan for investigating severe accident phenomena for light water reactors. It integrates various analysis modules into a single code.

SAMPSON was designed as a large-scale simulation system of interconnected hierarchical modules covering a wide spectrum of scenarios ranging from normal operation to severe accident conditions. Main features of the code are provided in Appendix B.

SCDAP/RELAP5

The SCDAP code is a package that has been developed since the 1970s and was subsequently thought to be internally coupled with RELAP5. As the development of RELAP5 branched into two main paths (i.e. NRC and DOE sponsored projects), the SCDAP development followed, too. Thus, different versions are currently available: SCDAP/RELAP5-3D, SCDAP/RELAP5Mod3.3, RELAP/SCDAPSIM. The three versions mentioned belong to Idaho National Laboratory (INL), Nuclear Regulatory Commission (NRC), and Innovative System Software (ISS), respectively. All the versions originated by the SCDAP/RELAP5 codes developed at the Idaho National Engineering & Environmental Laboratory (INEEL) for the NRC. The development of the RELAP5 series began at INEEL in 1975 while SCDAP development was initiated in the early 1970s with an integrated link to RELAP5 in 1979.

The structure of SCDAP code is based on the integration of three modules: SCDAP, COUPLE and MATPRO. SCDAP contains models for predicting core damage progression. COUPLE provides a two-dimensional finite element framework for detailed simulation of reactor vessel lower plenum and lower head of the vessel. Finally, MATPRO contains an extensive library of data and subroutines used to establish material properties and reaction rates. Moreover, SCDAP is integrated with the thermal-hydraulic module provided by RELAP5.

SOCRAT

SOCRAT is a Russian best-estimate severe accident code (current version is SOCRAT/V3). It models physical and chemical processes occurring during different phases of an accident including melt relocation from a reactor vessel to a concrete basement or core catcher. The best-estimate physical models and calculation modules of the SOCRAT code allow the simulation of a wide spectrum of thermal-hydraulic, physicochemical and thermo-mechanical phenomena. SOCRAT has been validated on many severe accident experiments. The code consists of three major modules: RATEG for the calculation of circuit thermal-hydraulics, SVECHA for the description of reactor vessel severe fuel damage phenomena, and HEFEST for the consideration of materials behaviour in the lower plenum and reactor vessel degradation.

TOLBIAC-ICB

The development of the TOLBIAC-ICB code was started in 2002, in the framework of an agreement between French organisations CEA and EDF, to provide a numerical tool for safety analysis related to molten core-concrete interaction (MCCI) in reactor situations.

In the event of a severe accident in a Pressurised Water Reactor (PWR), corium, a mixture of melted materials derived from the fuel, cladding and structural elements, appears in the reactor core. One of the scenarios of the severe accident assumes that corium may melt through the reactor pressure vessel and slump into the reactor pit after a certain period of time. The concrete structure of the reactor pit interacts with corium. This interaction needs to be quantified in order to determine the concrete ablation rate and the evolution of the wall thickness.

5.2.3.4 Complementary computer codes

Several computer codes exist in order to perform more detailed assessments of the manual actions specified in EOPs and SAMGs or sensitivity and uncertainty analyses. In principle, these tools are linked with deterministic accident analysis codes like the codes presented above.

The development of SIMPROC (see Appendix B for details) has been an initiative of the Spanish Nuclear Safety Council (CSN) in collaboration with Indizen Technologies (today NFQ Solutions) and the Technical University of Madrid (UPM).

SIMPROC provides capability to simulate the interaction between operators (guided by procedures) and the plant (represented by dynamic simulation models). This way, more comprehensive analysis tools can be developed in order to:

- evaluate the adequacy of emergency procedures for preventing the degradation of accidental situations;
- improve the probabilistic evaluation of human actions in PSA through a better treatment of their associated uncertainties, which, in many cases, dominate over other sources of uncertainty and cannot be ignored.

SIMPROC has been specifically developed for analysis of EOP. Modelling SAMG strategies is a more complex task which could require some extensions of the current SIMPROC capabilities.

For performing the important task of sensitivity and uncertainties analyses regarding severe accident analyses of SAMG measures, supporting tools are also available, e. g., DAKOTA (developed by SNL and part of the Symbolic Nuclear Analysis Package [SNAP]) and MCDET/SUSA (developed by GRS).

5.2.3.5 *Dedicated multi-dimensional code systems*

In order to examine single phenomena such as steam explosion, local hydrogen distribution inside containment and structural mechanics behaviour of components, often so-called dedicated 3D code systems are applied. Established 3D fluid dynamics codes are e.g. GASFLOW, TONUS, and the commercial codes CFX and FLUENT. GOTHIC code mentioned above has a 3D fluid dynamics capability, too. The application of CFD codes on the field of severe accident management measure could cover e.g. more detailed examinations of the effectiveness of PARs or of procedures for a forced mixing of hydrogen in a containment atmosphere. Within the family of structural mechanics codes there are e.g. CAST3M, ABAQUS, and the commercial code ADINA. For steam explosion investigation the MC3D code is often used.

5.3 Characterisation of SAMG assessment and mitigation actions

IAEA Safety Reports Series No. 56 [22] contains a section that provides specific suggestions for performing deterministic analyses of severe accidents. They include basic steps in developing input data, verification of the input models, main requirements for best-estimate severe accident analyses, assessment of uncertainties, performing simulations, evaluation and interpretation of physical phenomena in the results, and presentation of the simulation results. Those specific suggestions reflect the best practices in severe accident analysis and should be used as general guidance in the assessment of SAM measures.

This subsection deals with basic approaches and general methods used to characterise SAMG assessment. The focus is not on reiterating or expanding the severe accident analysis suggestions as given in [22], but rather on discussing the specific issues important to the characterisation of SAMG assessment and providing pragmatic guidance or suggestions for dealing with those issues.

5.3.1 *Important issues*

Informing SAMG and mitigation actions using analytical simulation is not a straightforward task and requires dealing with various constraints and challenges pertinent to numerical applications. In addition, the focus of the analysis needs to be different. Previous analytical work focused on identifying high risk

or scenarios that resulted in fuel damage; for example, of more interest to the EPG/SAGs for BWRs are those actions that prevent or mitigate core damage. Industry's position indicated that success states that can be addressed through procedural changes/updates are more important than detailed calculations of the low probability core damage events in these types of analysis.

Notwithstanding, some *important issues* relevant to the use of analytical simulation to inform SAMG are described below, together with discussion on the best practices to address them:

Issue 1 SAMG is symptom-based, not event-based. However, a numerical simulation requires a defined accident scenario or sequence, i.e. an initiating event with a defined sequence of availability and unavailability (failure) of systems and equipment. Numerically reproducing the symptom-based entry conditions of SAM guides from an arbitrarily selected accident sequence may not be meaningful for the purpose of assessing SAMG-specified actions. For a given mitigation action, simulations of a large number of accident scenarios are not practical and furthermore, dealing with the associated large uncertainties in numerical inputs and outputs from a large number of simulations could become unmanageable.

Ideally, the selection of scenarios to be simulated should be made from the results of both Level 1 and Level 2 PSA. In order to assess mitigative SAM measures or to predict releases of radionuclides, the results of Level 2 PSA should be used. In Level 2 PSA, all events leading to severe core damage or radiological release are grouped into a small set of "bins" such as "loss of all AC power", "loss-of-coolant accident", "containment bypass" and "shutdown state". Each bin contains events or accident sequences that have similar characteristics. A small set of representative accident sequences selected from each of the bins are simulated and the simulated results are considered to represent the behaviour of all the accident sequences within the bin. This methodology is often also used for the selection of accident sequences to be simulated for addressing severe accident issues and it can be used to assess the actions specified in SAMG.

For certain applications, the accident sequences within a bin and among other bins that result in the worst consequences with respect to a particular concern under examination (i.e. a figure-of-merit parameter) should be selected. For example, if the action to be assessed is related to mitigating the hydrogen consequences, the accident sequence that results in a prediction of maximum hydrogen among the Level 2 PSA results should be selected for simulation. If the action to be assessed is related to suppress containment overpressure, the accident sequence that results in a prediction of a significant containment overpressure should be selected for simulation. For actions that have impact on multiple concerns (or multiple figure-of-merit parameters) such as hydrogen generation, fission product release, and containment overpressure, more than one accident scenario or sequence defined within the Level 2 PSA may be selected for simulations.

The selection of scenarios to be simulated can be also based on expert judgement using the existing simulations that have already shown the sensitivity of the figure-of-merit output parameters to different scenarios. Sometimes, justification of a selected scenario can be made in combination with the strategies for varying other system and modelling parameters as part of uncertainty assessment (see the example given under Appendix C.2).

Issue 2 Using the established success criteria or limits alone to judge the outcome of an assessment may not be complete. Defining the success criteria depends on the purpose of the specific simulation (e.g. demonstrating the integrity of RPV) and the objective of the mitigation action under examination. Such criteria can be readily derived from the plant-specific SAMG. It should be realised that there might be no simple "success" or "failure" when the simulation results are directly compared with the success criteria. With the criteria, the purposes of the assessment are not only to assess whether an action specified in the SAMG will likely achieve its intended function, but also to assess its positive and negative impacts and provide insights and accident characteristics that are useful for the technical

support centre (TSC) experts to evaluate and then select or reject the action in a real event or for the SAMG developers and implementers to reconsider or refine the action in the next update. For situations where the simulated conditions are probably incomplete and contain large uncertainties, the emphasis should be on the latter, rather than a simple comparison of the simulation results with the “success” criteria.

Issue 3 **Treatment of simulation uncertainty is still a serious challenge for assessing SAM actions using analytical tools.** Simulation uncertainties come from various sources of approximations, such as the models of severe accident phenomena, the representation of physical geometries, and the user’s selection of modelling options as well as from the difficulty to predict the actual plant conditions during the accident represented in the simulation by initial and boundary conditions and assumptions on equipment survivability and availability, components failure criteria, human factors, etc. Informing SAMG actions through analytical simulation should be performed using the best-estimate approach. The associated uncertainties should be recognised, assessed through sensitivity analyses, and if necessary, quantified and taken into account in the assessment. In some cases, however, under adequate conditions, a thorough evaluation of uncertainties can be skipped if the assessment consists of a comparison between two situations subject to similar uncertainties. For example, a commendable practice in the evaluation of a mitigation action is to assess the effects of the action primarily based on the relative differences of key outputs between the simulation case including the action and the case without the action, rather than the absolute values of those outputs⁸.

Issue 4 **Difficulties exist in accounting for human and organisational performance (HOP).** The effects of HOP on the assessment of SAMG-specified actions are difficult to assess and take into consideration. In the EOP domain, the control room staff is trained to diagnose the plant condition, implement countermeasures, and bring the event into a controlled and safe state with certain technical supports. If a severe accident cannot be prevented, the plant-specific SAMG is called upon. After that, the diagnosis, prognosis, and decision making processes have changed. The TSC members diagnose the plant condition based on the available plant instrument readings provided from the control room and on the staff’s knowledge of the plant design, operation, as well as their understanding of severe accident phenomenology and progression. The TSC members consult the SAMG documents, evaluate the positive and negative impacts of the available mitigation actions, and recommend the selected action or actions to be implemented. Once approved, the control room staff and field operators are responsible for implementing the action(s) and provide information back to the TSC to assess the effectiveness of the implemented action(s).

For the purpose of crediting a selected action in a simulation, it is necessary to know how long it will take to implement the selected action once the entry conditions for the need of such an action are indicated from the plant instrument readings. The time interval, from an indication for the need of a mitigation action to the time the action has been implemented, reflects the HOP during the execution of SAMG. This time delay is influenced by many factors including: the reactor core and containment conditions indicated by the plant instrumentation, the availability of equipment (power and water sources), communication among the control room, the TSC, and the command-and-control line, the TSC performance, the decision making process, and the environmental conditions for the field operators to implement the selected action. The value of this time delay can be estimated based on the SAMG review, plant walk-throughs, tabletop exercises, and plant drills/exercises. Where this parameter is identified to

8 For example, a containment pressure predicted without a mitigating action could be high enough to reach the containment failure pressure limit whereas the predicted containment pressure with the mitigation action may not reach the failure limit. Rather than emphasising the containment failure or non-failure that were observed based on the absolute values of the predictions, which contain large uncertainties, it is more meaningful to consider the difference in the predicted pressures during the assessment of the action. If the difference is deemed small, it may not be conclusive that the mitigation action is effective in preventing the failure of the containment.

have a significant influence on the simulation results, a range of values that realistically reflect the HOP of the SAM crew under severe accident conditions should be set to cover the uncertainty in HOP.

Issue 5 **Consistency of simulation results needs to be ascertained.** In spite of a certain level of validation of the computer code(s) used for plant simulations, inconsistent simulation results can be sometimes found, especially when those codes with complex input decks are involved. Some combinations of input parameters and/or simulated plant conditions could result, among others, in numerical methods being used outside their validity range or in the use of incompatible options. As a consequence, the simulation code could produce some results which are inconsistent with the physical model equations implemented in the code. In the most favourable cases, a warning message will be issued by the code but in many others the user might not be aware of the problem. User qualification reduces the size of the problem but even highly qualified users are not free of this type of effect.

This problem is not exclusive of severe accident simulations. The same discussion applies to any simulation software, including for example thermal-hydraulic codes (see [20]). The problem is of particular importance when experimental data are not available for comparison with the simulation results as in the case of simulations used for informing SAMG actions and guides. In such cases, it is necessary to provide means for gaining confidence on the simulation results. Given the high level of uncertainty involved in severe accident phenomenology, one cannot be a hundred percent sure that the models implemented in simulation codes are a good representation of reality. However, it should be at least ensured that the numbers produced by the code are in physically acceptable range and represent actual solutions of the code equations. To this aim, a number of relationships between physical variables can be derived from the model equations and the simulation results can be post-processed to check whether they comply with those relationships.

This type of post-processing check can be efficiently performed if auxiliary software running in parallel with the simulation code is continuously checking the simulation results and raising warning messages whenever some inconsistency is found.

Partially connected with this issue is the user selection of the values of the parameters to tune the code models. They largely affect the calculation results. Generally, reasonable values to be used in the models can be derived only from appropriate experimental results.

5.3.2 *General approach*

In principle, a best-estimate approach (as discussed in [21] and [22]) should be used for severe accident analysis. Severe accident progression is influenced by numerous factors each having a certain uncertainty or variation. Determining which assumption is conservative in advance for severe accident analysis is difficult and sometimes impossible for multiple figure-of-merit parameters under consideration. More importantly, from an accident management perspective, it is highly desirable even though not necessary, to know what has actually happened in the plant and what are the realistic or best-estimated conditions occurring in the plant so that operators' actions designed to arrest the accident progression and mitigate the accident consequences can be implemented timely with proper protection of the personnel. Plant conditions estimated from a conservative approach may not be of much help and sometimes could even lead to wrong decisions.

The best-estimate approach calls for using current knowledge, representative accident scenarios, realistic plant data and instrumentation in the modelling of the plant, the availability of systems/components, the initial and boundary conditions. The best-estimate computer input models that realistically represent the plant design and configuration as well as the response time for operator actions should be used in the assessment of SAMG actions. In addition, various assumptions used in such an assessment can be established on the basis of the results of the plant-specific Level 1 and Level 2 PSA.

Advanced methods for the quantification of the uncertainties have been developed and tested. Although currently those detailed methods are often not applied routinely for the assessment of the uncertainty of severe accident analyses, detailed uncertainty analyses (e.g. see [23]) have been performed for certain situations where quantification of uncertainties is essential to understand the accident characteristics and then make any meaningful conclusion. It has to be emphasised that it is difficult to quantify uncertainties for all model parameters, in particular for parameters describing some severe accident phenomena. In any case, at least sensitivity studies for important parameters and modelling assumptions with varying relevant boundary conditions should be performed, in order to get a better understanding of the expected variation in the results. In addition, a comparison with computational results regarding similar severe accident scenarios of comparable plant designs done by external institutions and/or different computer codes, if possible, might be performed to gain confidence in simulation results.

A sufficiently detailed nodalisation of all components and buildings allows a realistic simulation of the NPP behaviour. The level of detail should be well balanced among the modelling of the reactor circuit, the core, the containment, and other buildings, also taking into account the necessary kind of results to be obtained and the related level of details. Furthermore, a balance has to be found by the analyst between the overall level of detail of the whole model and expected computation time.

The analyst actually performing simulations to assess SAM actions should at least become familiar with or have knowledge on:

- the NPP design and operation, including equipment and instrumentation called by SAMG;
- accident progression and severe accident phenomena;
- the safety of nuclear reactors including applicable national rules and guidelines;
- the plant-specific SAMG framework and documentation, including high-level strategies and detail instructions for specific actions that are selected to be assessed; and
- the computer codes used to support the assessment of SAM measures, including code qualification state, theory manual, user manual, input development and testing, and results evaluation and interpretation.

The code application experience of the analyst is also an important issue, because the user impact on the results is high for severe accident analysis codes. In addition, the team working on preparing the severe accident analysis input decks, evaluating simulation results, and doing quality assurance should have access to expert level knowledge on all these fields.

To inform SAMG and its specified actions through analytical simulations, the following approaches may be taken:

Approach 1: High-level assessment. Before a great deal of effort is spent into running computer codes, a high-level assessment is advisable in the early stage of a project involving analytical simulations. The scope of this high-level assessment is to use current knowledge and existing information to determine the need for additional simulations. This serves as a quick assessment process to confirm if the scope of the planned work is consistent with the established objective, and if the available toolsets and methods to be used are judged to produce the results that will help achieve the objective of the project. Equally important, the high-level assessment should be performed to see if other approaches exist with a better cost-benefit ratio and can be used to achieve the same project objective. If the necessity of the analytical simulations is confirmed, *Approaches 2 to 4* can be taken, which are described below.

Approach 2: Assessing an SAMG-specified action one at a time. For an individual action and its associated conditions requiring its implementation (e.g. the entry conditions specified in SAMG for a

strategy), simulations are performed to produce the entry conditions and then credit the action in the simulation in order to assess how the action influences the subsequent prediction of the accident progression and consequences. For comparison purposes, the same simulations are also performed without crediting the action. Although multiple simulations may be required to address important issues such as those discussed in Section 5.3.1 above, the focus of the assessment is on the feasibility and efficiency of the action and its positive and negative impacts. This type of assessment often covers one action at a time. Potential influences from other actions or a sequence of actions are not assessed. This type of assessment generates insights into the implementation of the individual action and produces one “building box” at a time, which, once accumulated, can be used to assess a set of SAMG actions or even the entire SAMG. The methodology that represents the current practices for this single-action assessment is highlighted in Section 5.3.3 below and examples of the application are given in Appendix C.

Approach 3: Assessing a set of SAMG steps or actions. Simulations are performed using severe accident computer codes to emulate a series of the steps and actions that are specified in the plant-specific SAMG. For comparison purposes, the same simulations are also performed without crediting any operator intervention. The assessment focuses on the effects of the multiple steps and actions being implemented in the simulation on the predicted accident progression and consequences, rather than on the effects of individual action. This type of simulation takes into account the interaction among the multiple steps and actions. The sequence at which the steps and actions are implemented in the simulation could also change the simulation results. The current practices and methodology for this multiple-actions assessment are given in Section 5.3.4 below and examples of the application are given in Appendix C.

Approach 4: Informing a set of severe accident guidelines or even the entire SAMG. Both the numerical results and qualitative observations obtained from the assessments mentioned above (i.e. *approaches 1 to 3*) can be used to understand and substantiate the strategies and specific actions documented in individual guidelines. Once sufficient assessments for individual actions or a set of actions are performed, the results form a database and could be used for informing the entire SAMG established for an NPP. This report does not compile any general methodology for this integrated approach. However, the following parts of the report can be used as general guidance for this approach:

- (1) Appendix D that provides examples of SAMG validation through tabletop exercises with support of severe accident simulations;
- (2) The key activities used for the evaluation of a plant-specific SAMG that are outlined in Section 3.2; and
- (3) The guidance in the resolution phase of Section 5.3.4.

5.3.3 Methodology for assessing an SAMG-specified action one at a time

This assessment focuses on a single action or a single system parameter or groups (sets) of them. The term "Action" is used in the following for the purpose of the assessment as described under *Approach 2* of Section 5.3.2 above.

The following basic steps only reflect the practices of some member countries to perform such assessments (see Appendix C for sample applications). They should be treated as a general guide, rather than a unique approach to inform SAMG through simulations. Different approaches do exist and they can be found in Appendices A, C and D. As presented below, these steps are described in a generic and pragmatic manner:

1. Specification of purpose of the analysis (e.g. quantification of mass flow rate through the x system, verification of the y step in an SAMG guide for loss-of-coolant accident (LOCA)

conditions, etc.), including specification of acceptance criteria to assess the success of the Action.

The purpose specification should be clear that the analysis is not only to assess whether the Action will achieve its intended function, but also to assess its positive and negative impacts and provide insights and rationales that are helpful for the evaluators to assess the Action.

An important aspect is to understand the Action specified in the SAMG. Questions should be asked such as why is the Action needed, what is the technical basis of the Action, what are the entry conditions under which the Action is called for, etc. The understanding can be obtained through a review of the plant-specific SAMG documentation as well as through the analytical simulation.

Specific success criteria (e.g. reducing the containment pressure before it exceeds a limit) and conditions should be defined and used carefully for the assessment of the Action. As pointed out under *Issue 2* of Section 5.3.1, there might be no simple “success” or “failure” when the simulation results are directly compared with the success criteria. Assessing the Action requires a full understanding of the simulation results and their limitations. Where numerical results are of large uncertainty, expert judgement with a support of sensitivity studies may prevail.

2. Selection of the computational tools.

What severe accident analysis computer code or sets of computational tools should be used depends on the purpose of the simulation. For a certain Action being simulated (e.g. switching on the air cooling fan to reduce the potential for formation of hydrogen pockets in containment), the tool or the tool sets selected should be capable of modelling the severe accident progression as well as providing sufficient details on the effect of the Action (e.g. calculation of hydrogen and its distribution in the containment). Most of the severe accident computer codes (see Section 5.2.3) are capable of modelling the severe accident progression and consequences in terms of fuel failure, core damage, hydrogen production, potential for containment breach and fission product release to the environment. Qualifications for their intended applications have often been performed and are documented.

However, assessing certain operator actions using these computer codes may be beyond their original application range or qualification of such an application is lacking. In this case, an assessment of the code applicability should be performed. The effort required for such an applicability assessment depends on the relevance of the existing code qualification to the simulation under planning, which could range from expert judgement to a detail assessment (e.g. involving the phenomena identification and ranking table (PIRT) process, and review of the code models in detail).

The purpose of the simulation directs the selection of the computer codes and it also influences the level of spatial and temporal details required in the development of the input decks for the selected codes. User’s knowledge on the code models and limitations often plays a crucial role in deciding the level of details to be modelled. Where necessary, the effect of different levels of modelling details on the simulation results may be quantified by a sensitivity study.

The complexity of the analysis and the intrinsic limitations of the codes could make it necessary, in some cases, to adopt a chain of codes to fully complete an analysis, with each code covering a specific technological area (e.g. thermal-hydraulic, core damage, hydrogen generation and combustion, structural mechanics, etc.). This approach poses the additional issues of the transfer and “translation” of the data from one code to the others, the spatial and timing correspondence between the codes and the combination of the uncertainties generated by the codes.

3. Identification of all relevant operation states of instrumentation and equipment dedicated to execution of the Action being assessed for the purpose of the analysis.

The instruments providing indications for the need of the Action, the equipment and the instructions used for operators to implement the Action, and the instruments monitoring the plant condition after the implementation of the Action are described in the plant-specific SAMG documentation. It should be noted that the severe accident codes do not predict the plant's instrument response, but only what the instrument would be measuring at the time. The procedural guidance is based on the instrumentation response using multiple indications and trends including assessing off-calibration conditions. For example, in order to improve V&V of the EPG/SAGs with analytical code modelling, the severe accident codes should have models for the off-calibration instrumentation conditions. It should also be realised that some of these instruments may not survive the severe accident conditions and if they do survive, some of their readings may be subjected to large error bars under harsh environmental conditions. Those situations, if arisen, may have to be considered in the simulation and assessment of the Action.

If necessary, some kind of failure mode and effect analysis (FMEA) may be executed in order to have a better understanding of the system response and vulnerabilities.

4. Identification and summary of credible initiating events and scenarios evolving into severe core damage, which are taken as the basis of the plant for the evaluation of design provisions and procedural/administrable measures for SAM.

The purpose of this step is to understand the basis of the plant-specific SAM measures. The results of Level 1 and Level 2 PSA for the plant should be reviewed with a focus on the initiating events and accident sequences used in the Level 2 PSA, particularly those leading to a challenge to the containment and a radiological release. SAMG is symptom-based, not event-based. Nevertheless, performing this step with a summary of accident sequences used in the Level 2 PSA is essential for establishing the technical basis of the analytical simulation, for example, to answer the question about why a particularly accident scenario has been selected in the simulation for the assessment of the Action. As discussed under *Issue 1* of Section 5.3.1, a small set of the representative accident sequences (or scenarios) as used in the Level 2 PSA may be selected for the simulation.

5. Development of the simulation matrix for the assessment of the Action.

This step contributes to an overall planning process for simulations to be performed and later to an integral evaluation of all simulation results. Based on steps 1 to 4 above, the simulation matrix defines the *base cases* and the *sensitivity cases*. The *base case or cases* specify the accident scenario or scenarios to be simulated, including initial and boundary conditions, availability or unavailability of structures, systems and components, best-estimated time delay for the Action to be implemented in the simulation, important modelling assumptions (physics of accident progression, operator actions, equipment performance, etc.), and best-estimated values of the key parameters that are expected to have a significant influence on the simulation results. The *sensitivity cases* define the variants from the *base cases*. Identification of key parameters may be based on the results of any existing formal process used for the qualification of the computer code or expert judgement for this application or the combination of the two. The assessment of the Action is not purely a numerical exercise. The number of the simulations specified in the simulation matrix should be controlled in a practical and manageable level. Each of the variables given in the simulation matrix should be selected such that it constitutes a simulation of the results, which are clearly useful for the assessment of the Action. The process used to develop the simulation matrix and the rationale for the definitions of the base and sensitivity cases should be documented.

Section 5.3.1 (see *Issue 1*) provides a basis for the selection of accident scenarios to be used in the setup of the simulation matrix. Further on that basis, qualitative or quantitative arguments are often used to identify the scenarios where the most demanding conditions in terms of feasibility or effectiveness of the Action are expected. If a single scenario cannot be identified to satisfy the key aspects under consideration, a small set of scenarios covering the foreseen unfavourable conditions for the Action to be

implemented should be selected. For the selected scenario(s), the most significant uncertainties, including time delays (e.g. operator delay) which could result in significant variations in the Action outcome, should be considered during the development of the simulation matrix.

6. Analysis and interpretation of the simulations for each of the cases defined in the simulation matrix:
 - a. Based on the simulation matrix, setting the input model. In general, a best-estimate input model is set to realistically represent the plant design and response to severe accidents.
 - b. Simulation of the defined scenario without the Action to be analysed. This case is normally treated as a base case without crediting the Action or so-called “unmitigated case”. The results will be compared with the “mitigated case” where the Action is included in the simulation to mitigate the accident consequences.
 - c. Examination of the results of the “unmitigated case” (Step 6b above) in order to specify conditions for initiation of the Action. The examination helps verify if the setpoints indicating the SAMG-specified entry conditions of the Action are reached in the simulation, the equipment required to implement the Action remains operational (e.g. presenting no core debris in the flow path and having sufficient water level and/or net positive suction head (NPSH) for a pump-driven recirculation action). The examination of the simulation also looks into the environmental loading conditions for the equipment to operate and the environmental conditions of the pathway for the operator to access and implement the Action, if a field operation is required. This step may have to consult with the plant-specific SAMG documentation to check if the operator has sufficient information necessary to initiate the Action (e.g. the relevant setpoints, instrument and control [I&C] values including delays, and step-by-step instructions to operate the equipment under harsh conditions and possibly beyond its normal usage). The specific information and the simulated results are useful for assessing whether the Action can be initiated and how much time delay is reasonable for the Action to be implemented in consideration of the estimated environmental conditions as well as the human and organisation performance (HOP) of the SAM crew in terms of time required to diagnose the plant condition, select and evaluate the Action, approve and implement the Action during SAM.
 - d. Setting boundary conditions of the Action into the model. This step sets the specific point of the evolution of the event to start simulation of the Action, taking into account differences between the model and reality, including delays in media delivery, curves of changes of parameters (e.g. flow rates), setpoints of control (e.g. setting a higher-than-normal temperature limit to allow a pump to run under severe accident conditions).
 - e. Simulations of the defined scenario including the Action with potential variations to address uncertainties including an earlier or delayed initiation of the Action and other key variables identified and specified in the simulation matrix.
 - f. Detailed check (using outputs of the simulations) of environmental conditions in the location where the means for realisation of the Action are placed while verifying that limits for realisation of the Action are not violated (e.g. an ambient temperature does not exceed the qualification limits, a surface temperature of a structure such as an air filter does not reach the auto-ignition limit in a hydrogen-air-steam mixture, and radiation doses do not prevent staff from reaching specific location for performing the Action). This check or examination of the simulation results provides detailed information that is essential for assessing the feasibility of the Action.

- Can the Action be implemented under the simulated environmental conditions in consideration of the entry conditions, I&C systems and instructions given in the plant-specific SAMG documentation as well as the uncertainties identified?
 - What are the effects of an earlier or delayed initiation of the Action?
 - Does the assumed time delay used in the simulation for initiation of the Action realistically reflect the HOP of the SAM crew based on their training, drills and exercises or real event experience encountered to require using the plant-specific SAMG?
 - Does the implemented Action achieve its intended outcome as indicated in the plant-specific SAMG based on the simulation results as well as expert judgement?
 - Are all the positive and negative impacts of the Action quantified using the simulation results or qualified by expert judgement?
 - Are there any areas that require special attention to implement the Action in a real event based on the experience gained from this evaluation exercise?
 - Is there any feedback to the current plant-specific SAMG, particularly relating to the Action being evaluated?
8. Documentation of the simulation process, results, specific investigation and overall evaluations of the Action, positive and negative effects identified for the Action, key observations, recommendations and conclusions, if any. If necessary, responses to each of the questions raised in Step 7 should be documented in detail with supporting evidence (e.g. tables and plots of the simulation results, relevant experimental data, other computer code simulations, etc.).

An illustration of application of the above methodology for simulations of a specific Action is given in Section C.2.1 of Appendix C.

5.3.4 Methodology for assessing a set of SAMG steps or actions

Unlike the assessment of one mitigation action at a time, this assessment (*Approach 3* as described in Section 5.3.2) takes into account the interaction and sequence among the multiple steps and actions specified in a particular guide or different guides with the plant-specific SAMG package. For example, a Severe Challenge Guide (SCG) documents the strategies to mitigate the fission product releases when the measured radiation exceeds a pre-determined limit. The strategies may include implementation of a set of steps and actions such as isolation of containment penetrations, depressurisation of containment by restoring some air cooling units into service to condense steam, etc. At the same time, other mitigation actions such as filling of the reactor cavity with water to prevent the failure of the RPV, as part of early response to the accident, may still be in execution or have been already completed. To assess the efficiency of such multiple steps and actions, a more integral approach is required.

Again, the methodology described in this subsection reflects the practices of some member countries and should be treated as general guidance, rather than a unique approach to inform multiple SAMG actions through simulations.

In this subsection, the Actions are referred to as the SAMG-specified multiple steps and actions selected to be simulated. The general process and the methodology specified in Section 5.3.3 for assessing the SAMG-specified individual Action can be still used, wherever applicable. On this basis, the methodology for the assessment of the Actions is further built upon with the following assumptions:

- Development of the plant-specific SAMG with fixed strategies has been completed and its documentation is at least in draft and available to the assessors.

- Computer codes and corresponding models are available, capable to simulate the accident including operator intervention actions. Obtaining a simulation system capable for automatically developing dynamic event trees is highly advisable. Likewise, availability of a software package with capability to model SAMG actions in interaction with plant simulation would make the analysis much more efficient.
- Full-scope information about operation conditions is available, especially:
 - Guidance to assess real response of operator (see the discussion in Section 5.3.1 for HOP during the execution of SAMG).
 - Overview of monitoring system to be used in severe accident conditions including delays between reaching physical value and signalisation in the control room, and knowledge on instrumentation survivability and uncertainties under severe accident conditions.
 - Specification of delays between signalisation and actuation of corresponding system, including time delay due to decision making and execution of selected actions by the SAM crew (e.g. role of the TSC) and impact of its activities to the time delay.
 - Characteristics of the monitoring system regarding resistance to environmental conditions (qualification limits).

The assessment activity may be split into the three phases:

- 1) Preparation phase
- 2) Assessment phase
- 3) Resolution phase

The Preparation and partially also the Resolution phases typically do not need direct analytical support, but require access to, and consultation with, a large scope of analytical database of severe accident simulations. They also need to be supported by detailed and deep understanding of the plant design features and the associated severe accident progression and phenomenology. All these three phases are briefly described below.

Preparation phase

During this phase, the complex list of accident scenarios should be prepared to be used for SAMG validation. As discussed in Section 5.3.1, SAMG is symptom-based, not scenario-based. However, a numerical simulation requires a defined accident scenario or sequence. The accident scenarios defined in the Level 2 PSA should be the main source for consideration and selection for simulation. In addition to the methodology given in Sections 5.3.1 to 5.3.3, the scenarios should be defined in such extent that:

- At least one scenario representative of the release categories considered in the Level 2 PSA is included, leading to entry into each single guide of the SAMGs. The intent is to assess a set of SAMG steps and actions with coverage of scenarios that best represent the plant risk as a part of SAMG evaluation.
- The selected initiating events to be simulated should be relevant to the Actions under assessment and are expected to have the most direct challenge for the Actions to be implemented and effective. This may require a sensitivity study to confirm the adequacy of the scenario selection.
- For each initiating event several modifications of accident evolution should be considered, reflecting variations of initial and boundary conditions, leading to significantly diverse status of the unit (plant) in the transition to severe accident state (e.g. several different locations of break in LOCA initiating event, loss of heat removal due to different causes etc.).

Steps 1 to 5 of Section 5.3.3 have described a process for the preparation phase, i.e. specification of purpose, selection of computational tools, identification of relevant operation states, identification of credible initiating events and combination of events with additional failures, and development of the simulation matrix including necessary sensitivity cases. This process can be used to meet the above guidance and expectations.

Assessment phase

This phase is based on direct link to analytical simulation, either in "real time" using a full-scope simulator in "computer time" using severe accident analysis codes, or off-line using documented and summarised results of dedicated analyses. The off-line approach has to rely on high level of expertise of the specialists providing information about accident evolution in response to accidental conditions and operators/systems interventions. The on-line simulations may require using the software system capable for performing simulations in an interactive mode or using the restart capability of the computer codes to simulate a sequence of changes in action.

For each of the scenarios included and specified in the preparation phase (e.g. as defined in a simulation matrix) the following basic steps should be taken in the given sequence:

- 1 Analysis of the initial phase of the scenario up to transition into the SAMG, check of the transition conditions, and simulation of operator activity dedicated to transition from EOPs to SAMGs.
- 2 Interpretation of the calculated data from the point of view of operator, i.e. to prove that the conditions for entry into SAMGs are identified by the control room, taking into account the SAMG-specified setpoints, I&C values including delays, delays of operator response and action, readiness of the system, environmental conditions for the system to operate, etc. In addition, whether the transition to SAMG can be initiated at the time specified in the scenario should be assessed.
- 3 Step-by-step simulation of the event evolution and harmonising with operator activities (i.e. performing the SAMG-specified steps and actions by following the SAMG-specified diagnosis and decision processes). For each step, it should be demonstrated that the operator has access to sufficient information necessary to perform the activities. More specifically, the following tasks may be taken:
 - a) Adjustment of boundary conditions for continuation of the simulation or incorporation of them into the simulation (specific point of the evolution of the event to start the simulation of the operator intervention and system actions, taking into account differences between the model and reality, especially delays in media delivery).
 - b) Simulation of the next evolution of the scenario including operator intervention with potential variations to address uncertainties, generally taking uncertainties in both directions unless there is a clear desire for taking them in one direction that is driven by the objective of the assessment. Some uncertainties can be addressed by using bounding values of the uncertain items taken in the direction unfavourable for the implementation and efficiency of the Actions. In other cases it will be necessary to take into account several possibilities, which could result in significant differences in the subsequent evolution of the scenario. These cases include the occurrence of stochastic phenomena, decisions to be taken by the TSC, variability in the timing of sequence events and so on. In these cases, characterisation of the uncertainties in terms of probability of each analysed alternative (conditioned to the existing boundary conditions) is essential in order to characterise the final expected frequency of non-stabilised scenarios. The use of a dynamic event tree simulation system in

interaction with severe accident analysis computer codes with capability to model operator actions as required by SAMG could make this stage of the analysis much more efficient.

- c) Detailed check (using outputs of the analysis) of environmental conditions in the location where the Actions are placed while verifying that limits for operation are not violated (e.g. ambient temperature does not exceed the qualification limits, radiation doses do not prevent staff from reaching specific location for performing the Actions). If such limits are exceeded, the involved systems and actions cannot be credited or a further investigation is required.
 - d) Interpretation of the scenario analysis regarding the acceptance criteria for the Actions under evaluation. If the criteria for stabilisation of the accident are satisfied (i.e. the SAMG exit criteria are reached), proceed with the next analysis case.
 - e) If the simulated scenario evolves into an uncontrolled accident (i.e. a stabilised state is not reached), finalise the simulation with instructions for more detailed analyses or assessments to understand why the Actions being simulated fail to achieve the intended outcome, including quantifying the frequency of the scenario. If some aspects of the SAMG guidelines can be optimised without reconsidering the whole set of SAMG, return to step 3a above. If not, seek other means of validation.
- 4 Integral evaluation of the scenarios, assessment of efficiency of the Actions, assessment of potential modification and enhancements to the SAMG to reach increased margins to acceptance criteria and/or to support the success of the SAMG execution. The guidance given under Step 7 of Section 5.3.3 should be used, to the extent practicable, for this integral evaluation.
 - 5 Documentation of the analysis, including summary of the outcomes to be generalised in Step 4 after all the scenarios have been analysed. The documentation should include simulation process, results, individual and overall evaluations of the Actions, key observations, recommendations and conclusions if any.

Resolution phase

The resolution phase should evaluate the adequacy of the SAMGs and their ability to mitigate consequences of the severe accident. This could be a further integral evaluation as performed in Step 4 above in the assessment phase, but with an emphasis on the overall feasibility and efficiency of the actions specified in the plant-specific SAMG. The evaluation itself should consist of three pillars:

- 1) **Diagnosis capability.** Evaluators should prove that there is convincing reason to assume that the SAM crew will be able to identify the status of the plant for the plausible severe accident conditions and, moreover that the uncertainty and survivability of instrumentation in a severe accident will allow necessary, timely and appropriate decision making.
- 2) **Actions setting.** Evaluators should prove that the key actions intended to be used within the SAMGs are qualitatively appropriate. It means that all the actions are able to meet desired functions and objectives within expected environmental conditions and expected times of operation. Moreover, any mutual impact among the actions and corresponding instrumentation and equipment does not limit or challenge meeting the desired functions and goals of mitigation strategy.
- 3) **Human factors.** Evaluators should prove that for all the reasonable combination of actions and the sequence of implementation of the actions within the considered scenarios, sufficient time frames exist for operator actions including a reasonable delay coming from reading measured parameters, execution of other guidelines or procedures if needed, communication among the SAM teams (especially among the control room staff, the TSC members, and the site emergency managers), decision making, or any technological reasons.

The above three pillars are established based on not only the analytical simulations, but also the overall feedback among the designers of instrumentation, equipment and dedicated systems, the developing team of SAMG, and the SAM personnel who have SAMG training and drill/exercise experience. Important findings from the resolution phase should be reviewed and, if necessary, assessed by an engineering board or a group of experts in which all the design, development and evaluation teams are represented.

If the resolution phase concludes that some aspects of the SAMGs or of the plant systems should be further optimised, a new iteration of the assessment process, including assessment of specific Actions, should be initiated after implementation of the modifications. Hopefully, only some aspects of the analysis will need to be reconsidered. This iterative process will continue until the set of SAMGs reaches an acceptable level of optimisation.

As pointed out in Section 3.2, analytical simulation is one of the activities required for the overall evaluation of a plant-specific SAMG. Due to uncertainties and challenging issues such as discussed in Section 5.3.1, analytical simulation alone may not be enough to make affirmative conclusions on the strengths and weaknesses of the SAMG. Such conclusions should not be made until all necessary activities (e.g. as listed in Section 3.2) have been completed. Therefore, any recommended improvement or optimisation of SAMG should come from a true overall evaluation involving not only the activity of analytical simulation of the SAMG actions, but also others activities such as an independent expert review of the SAMG documentation and independent observations and evaluations of plant severe accident drills/exercises.

5.4 Documentation of the simulation results

Informing SAMG and actions through analytical simulation should be documented. The documentation is not only a record of the simulation, but also a process of re-assembling or reaffirming all relevant information and data in support of meeting the objective of the simulation. Furthermore, the documentation is a self-check and integration process and it, once completed, facilitates independent verification and/or peer reviews.

The level of details given in a report or paper depends on the purpose of the documentation. For typical simulations as outlined in Sections 5.3.3 and 5.3.4 to support an evaluation of SAMG actions, the documentation may have to document every step or phase as described in those subsections. In general, the documentation should provide at minimum the following:

- objective of the simulation(s);
- description of SAMG steps and actions to be simulated and evaluated;
- the computational tools used and their applicability to the simulation(s);
- the simulation process including the selection of accident scenarios, the input decks, and the simulation matrix with justification of key assumptions and parameter value settings with their variations to address uncertainties;
- the simulation results, particularly those that could be used as figure-of-merits to support the evaluation of the SAMG actions (e.g. containment pressure for an SAMG action of restoring the containment heat sink) and their positive and negative impacts on accident progression and consequences;
- interpretation of the simulation results;
- evidence of self-check and, if necessary, independent verification and peer/expert reviews;
- overall evaluation of the SAMG actions with conclusions, and recommendations if any.

If the documentation is intended to be available in the TSC room (e.g. as the essential information of a Technical Support Guide of a PWR SAMG as discussed in Section 4.3.2) and consulted by the TSC experts to support their duties, a summary version of the document is desired. The summary may contain tables and self-explanatory graphs with key messages including observations from the simulated results and their limitations. These summarised results should be confirmed by independent verification and expert reviews.

5.5 Use of the simulation results

The analytical simulations of key actions specified in a plant-specific SAMG and the associated documentation or a set of the documentation are useful, as guidance or background information, for:

- further development or enhancement of the SAMG;
- support of SAMG verification and validation;
- confirmation of readiness of the actions;
- training of the personnel responsible for SAM (see [4]);
- preparation of SAMG drills and exercises;
- consultation by the TSC experts to perform their duties in a real event (namely, diagnose the plant condition, select and recommend viable mitigation actions to be implemented while considering positive and negative impacts, and evaluate the effectiveness of the actions that have been implemented);
- verification of reliability and performance of the dedicated systems (feedback for designers, if any).

However, the use of the severe accident simulation results should be limited to the intent and purpose specified in such an analytical investigation. Using the simulation results from a specific severe accident analysis beyond its original purpose is not generally commendable. The reason is that in severe accident analysis, a different purpose often leads to a different choice of modelling options including accident scenario selection and key parameter value setting.

As pointed out before, the established computer codes for modelling of severe accidents still have significant uncertainties. For this reason, the assessment of SAMG-specified actions through computer code simulations or simulators must recognise the inherent limitations of this approach. Therefore, the analytical simulations that are discussed in this report are primarily intended to provide *support* to an evaluation of SAMG actions, rather than a *direct demonstration* of success or failure by one simulation or a large number of simulations.

Engineering judgement is a part of interpretation of the simulation results and the overall evaluation of the SAMG actions. Various measures can be in place in order to reduce the influence of inadequate judgement and achieve reasonable confidence in the assessment of the effectiveness of SAMG through analytical simulation. These measures include, but are not limited to:

- obtaining a full understanding of the principle and basis on which the plant-specific SAMG has been developed;
- having detailed knowledge of the computational tools used, including their range of applicability, modelling approximation, type of theoretical equations solved, source and uncertainty of empirical correlations employed, and relevant validation or benchmarking exercises;
- checking consistency of simulation results in terms of compliance with the theoretical equations implemented in the code in order to avoid numerical errors or inadvertent effects of incompatible code options, among others;

- conducting independent verification and review of the simulations, particularly in the areas of computer code limitations, simulation uncertainties, code user effects in selecting the simulation scenarios and making assumptions due to limited knowledge and data;
- inviting experts in SAMG development, severe accidents and modelling, and the computer codes to participate in the evaluation of SAMG or review the evaluation;
- performing a detailed sensitivity study and/or uncertainty analysis, if necessary, to have a better understanding and quantification of the uncertainties that exist in the simulations;
- benchmarking the analysis using different methods and/or computer codes;
- using analytical simulation in combination with other methods such as tabletop exercises and plant drills/exercises to inform SAMG actions.

6. PWR Experience – Assessment of PWROG SAMG-Specified Actions

6.1 Background

During the development of the enhanced Pressurised Water Reactor Owners' Group (PWROG) severe accident management guidance (SAMG), a detailed review of the SAMG bases was performed. This review revealed several areas of severe accident guidance where the EPRI Technical Basis Report (TBR) [19] did not provide a basis for specific strategy implementation. In the current draft version of the PWROG severe accident management guidelines (SAMGs) [18], scoping MAAP analyses and engineering judgement were used to make assumptions about the correct guidance for the applicable scenarios.

As part of the programme entitled “Support for Development of Enhanced SAMG Technical Basis”, the PWROG was able to review and interact with the team developing the EPRI TBR. The extent to which the EPRI TBR documented the SAMG bases was limited to the knowledge of SAMG actions and strategies that were available at the time and our expectations of what additional actions would be required in light of post-Fukushima lessons learnt. Given that the programme, entitled “Development of Enhanced SAMG”, has now completed the first draft revision of the PWROG SAMG, gaps in the technical bases offered in the TBR have been identified. These gaps are considered to be only applicable to PWR containment designs as they are all related to mitigation strategies for protecting against containment overpressure and mitigation of hydrogen in containment. In order to close some of the identified gaps, a programme involving severe accident simulations and analyses has been authorised and started in August 2015.

6.2 Analysis that supports severe accident management guidance strategies

The areas of the PWROG SAMG that will be bolstered with additional severe accident analysis are outlined below:

- Strategies for Managing Combustible Gases in the Short and Long Term

MAAP analyses will be performed to investigate the impact of containment design on the guidance for handling containment threats due to hydrogen. MAAP analyses will be performed for all containment and cavity designs (i.e. both large dry as well as small ice condenser containment designs). These MAAP analyses will be used to determine a detailed strategy for how and when the various containment designs should be vented to reduce hydrogen in the long term, and determine if this is a viable option. Containment cooling methods, cavity design, containment design and availability of igniters will be some of the important parameters that will be investigated.

- Impact of Molten Core-Concrete Interaction (MCCI)

Another area that will be investigated using MAAP analyses is the impact of MCCI on containment pressurisation, production of hydrogen & carbon monoxide and resulting ablation depth and how this relates to other ongoing mitigation strategies (e.g. use of containment sprays and containment venting). MCCI predictions are highly dependent on the composition of the concrete beneath the vessel; this will be an important element of consideration.

- Guidance for Venting Containment

The current PWROG SAMG guidance for venting containment lacks specificity for several areas. The PWROG will execute a series of MAAP analyses for the various PWR containment and cavity types and will address the following items:

- the pressure band that should be used for opening and closing containment vents when venting for pressure control;
 - this will also consider the PSA insights related to cycling the containment vent valves;
- determine if containment sprays should be started (if possible) to reduce fission product releases in conjunction with venting (for pressure control or for hydrogen);
 - this will also investigate the impact of this strategy if the containment is steam inert;
- investigate any potential benefits of venting while the core is still in-vessel or while the core is ex-vessel but submerged.

6.3 Characterisation of uncertainties

As part of the PWROG effort to use severe accident analyses to improve the technical basis for SAMG strategies it is recognised that uncertainties will be important to consider. In many cases the conclusions from the individual MAAP analyses are only as good as the assumptions and correlations that are built into the code and the case inputs. The PWROG will be performing and investigating these areas of uncertainty and will consider them when developing the details of the strategy implementation guidance. This discussion will include a qualitative examination of the impact of these model uncertainties on the behaviour of hydrogen generation, ex-vessel relocation, MCCI, fission product distribution, and thermal-hydraulic conditions. The initial uncertainties will be characterised based on the most recent version of the MAAP5 Applications Guidance. Further, the categorisation will indicate, at a high level, those uncertainties in the model that have a high influence on the trends (i.e. the severe accident phenomenological events) identified for the strategy development MAAP cases.

The PWROG also recognised the possibility that a phenomena identification and ranking table (PIRT) analysis may be beneficial to understand the uncertainties related to these SAMG strategies. If necessary, the PWROG will identify and rank the SAMG specific uncertainties using a structured PIRT methodology. The uncertainties must be accounted for due to the nature of the outputs generated as part of the SAMG tasks. Of particular interest are the following:

- Mitigation of hydrogen risk
 - Limitation of the hydrogen deflagration pressure characterised by adiabatic isochoric complete combustion (AICC) pressure and prevention of hydrogen detonation
 - Conditions of hydrogen flame acceleration which could induce dynamic pressure loads
 - Maximum thermal loads on the containment shell and in containment for design of severe accident materials
 - Influence of activation of the spray system
- Justification of ex-vessel melt stabilisation concept (MCCI)
 - The range of corium release conditions from the vessel
- Prevention of containment over-pressurisation
 - Rapid pressure increases in the containment (including fuel dispersal interaction)
- Limitation of radiological releases
 - Highest containment radiological source term

Deterministic sensitivity studies may be provided in addition to the best-estimate and uncertainty analyses to supplement the discussions related to these issues, as necessary, for all containment and cavity designs.

7. Summary and key messages

As an incorporation of lessons learnt from the Fukushima Daiichi nuclear accident, implementing and enhancing the existing severe accident management (SAM) programmes in NPPs, while demonstrating their effectiveness, becomes an important post-Fukushima activity. The development/update and implementation of generic and plant-specific severe accident management guidance (SAMG) and the integration of the SAMG with other plant procedures such as emergency operating procedures (EOPs) and guidelines such as Emergency Mitigating Equipment Guidelines (EMEGs), FLEX Support Guidelines (FSGs) and Extensive Damage Mitigation Guidelines (EDMGs) are an essential part of the SAM programme. Therefore, evaluation of SAM largely involves verification and validation of SAMG and its integration with other procedures and guidelines.

This Nuclear Energy Agency Working Group on Analysis and Management of Accidents (NEA WGAMA) report addresses the topics of SAMG verification and validation. Diverse practices exist to conduct SAMG verification and validation using methods such as expert judgement, tabletop exercises, plant walk-throughs, plant drills/exercises, simulators, field training, analytical simulations, etc. Having described SAMG verification and validation in general and current practices in this regard, this WGAMA Task Group decides to take analytical simulation, which is considered one of the means to assess SAM effectiveness, for further discussion. Therefore, this report first provides an overview of the current SAMG status, regulatory requirements and guidance, issues related to SAM evaluation, recent Pressurised Water Reactor Owners Group/Boiling Water Reactor Owners' Group (PWROG/BWROG) generic SAMG updates, and current diverse practices related to SAMG verification and validation in the member countries. Then it focuses on the current toolsets, general methodologies and guidance on use of analytical simulation to inform SAMG and its specified actions.

Established severe accident analysis computer codes applicable for informing SAMG and assessing SAM actions are reviewed in Appendix B. Specific examples demonstrating the use of the guidance given in this report are provided in Appendix C. Examples of integrated assessments as part of SAMG validation using well-designed, full tabletop exercises supported by analytical simulations are given in Appendix D.

This WGAMA Task Group would like to deliver the following key messages, some of which (text below in *italics*) are considered as commendable practices in the field of SAMG evaluation devoted to increasing confidence in SAM actions:

- 1) Symptom-and-knowledge based guidance provides an optimal approach to prevent and mitigate severe accidents. Symptom-based guidance requires adequate knowledge and training to diagnose plant conditions and to identify options that implement viable countermeasures to prevent and mitigate severe accidents. Informing SAMG and actions through analytical simulation is considered as an accumulation of such knowledge.
- 2) Analytical support plays an important role in the development, implementation, review, evaluation, maintenance and periodic update of generic or plant-specific SAMG, particularly in terms of understanding the phenomenology of severe accidents and their plant-specific symptoms revealed by plant conditions and available instrumentation.

- 3) A review of the current severe accident computer codes and other complementary computational toolsets (see Section 5.2.3 and Appendix B) indicates that they have been remarkably advanced and extensively tested in recent years. These codes offer capability for modelling key phenomena, physical processes and various progressions of a severe accident with the influences of operators' actions. *Using the state-of-the-art computational tools for assessing severe accident progression and consequences with and without operators' actions allows utilisation of the current knowledge and research data in optimisation of SAM actions.*
- 4) *Informing SAMG and actions through analytical simulation is a practical and commendable practice, which supplies the personnel who assess the SAMG with detailed information required to understand and characterise the SAM strategies and the associated implementing actions in such a way that the feasibility and efficiency of those actions under severe accident conditions can be assessed (see Appendix B for examples).*
- 5) Analytical simulation alone may not be sufficient to assess SAM effectiveness. *In addition to the insights obtained from the simulations of SAM actions, assessing SAM effectiveness should come from an integral evaluation that takes into account all inputs such as from the review of SAMG documentation, staff qualification and training results, and validation activities such as tabletop exercises, plant walk-throughs, and drills and exercises, etc.*
- 6) Analytical methods (such as simulations using computational toolsets, e.g. severe accident analysis computer codes) form part of the SAMG basis, but expert opinion and understanding of plant systems and capabilities are equally viewed as important in the development and evaluation of SAMG.
- 7) *The purposes of assessment of an SAMG-specified action are not only to assess whether the action will likely achieve its intended function, but also to quantify the environmental conditions under which the action is being implemented, assess its positive and negative impacts, and provide insights and rationales that are useful for the technical support centre (TSC) experts to evaluate and then to select or reject the action or make a rule for its correct timing and necessary prerequisites for the success in a real event, or for the SAMG developers and implementers to reconsider or refine the action in the next update.*
- 8) Numerically reproducing the symptom-based entry conditions prescribed in a SAM guide from an arbitrarily selected accident sequence may not be meaningful for the purpose of assessing SAMG-specified actions. *The selection of scenarios to be simulated should be made with consideration of the Level 2 PSA results, figure-of-merit (output) parameters under examination, strategies for varying other modelling parameters as part of uncertainty assessment, existing simulations that have demonstrated the sensitivity of the output parameters to different scenarios, and expert judgement (see Section 5.3.1).*
- 9) Treatment of simulation uncertainty still remains a serious challenge for assessing SAM actions using severe accident analysis computer codes (see Section 5.3).
 - a. Simulation uncertainties come from various sources of approximations, such as, in the models of severe accident phenomena, the representation of physical geometries, and the user's selection of modelling options and assumptions related to anticipated plant conditions in accident sequences such as initial and boundary conditions, equipment survivability and availability, components failure criteria, human factors, etc. Time uncertainties in operator actions and in occurrence of phenomena are of particular importance. Human action timing is further considered in item 10 below.
 - b. *Informing SAMG actions through analytical simulation should be performed using the best-estimate approach. The associated uncertainties should be recognised, assessed (e.g. by*

- sensitivity analyses, comparison with experiments and calculations using different computer codes, or integrated statistical uncertainty analyses), and if necessary, quantified and taken into account in the action assessment.*
- c. *In addition to any necessary uncertainty assessment, a commendable practice in the evaluation of a SAM action is to assess the effects of the action primarily based on the relative differences of key outputs between the simulation case with the mitigating action and the corresponding unmitigated case, rather than the absolute values of those outputs.*
 - d. *In recognition of large uncertainties in severe accident analysis, engineering judgement is a part of interpretation of the simulation results and the overall evaluation of the SAMG actions. Various measures can be put in place in order to reduce the influence of inadequate judgement and achieve reasonable confidence in the assessment of the effectiveness of SAM through analytical simulation. These measures are discussed in Section 5.5 of this report.*
- 10) The time interval, from an indication for the need of a mitigation action to the time the action has been implemented, reflects the human and organisational performance (HOP) of a SAM crew during the execution of SAMG (see Section 5.3.1).
 - a. This time delay is influenced by many factors including the reactor core and containment conditions indicated by the plant instrumentation, the availability of equipment (power and water sources), communication among the control room, the TSC, and the command-and-control line, the TSC performance, the decision making process, and the environmental conditions for the field operators to implement the selected action.
 - b. The value of this time delay can be estimated based on the SAMG review, tabletop exercises, plant walk-throughs, and plant drills/exercises. Where this parameter is identified to have a significant influence on the simulation results, a range of values that realistically reflect the HOP of the SAM crew under severe accident conditions should be set to cover the uncertainty in HOP.
 - 11) The methodologies given in Sections 5.3.3 and 5.3.4 and examples given in Appendices C and D of this report reflect the current and desired practices of some member countries to inform SAMG and actions using analytical simulations as one of the means to assess SAM effectiveness. They should be treated as a general guide, rather than a unique approach in this field.
 - 12) *The use of the severe accident simulation results should be limited to the intent and purpose specified in such an analytical investigation. Using simulation results from a specific severe accident analysis beyond its original purpose is not generally commendable.* The reason is that in severe accident analysis, a different purpose often leads to a different choice of modelling options including accident scenario selection, key parameter value setting, and uncertainty treatment.
 - 13) *In addition to various computer code simulation activities currently devoted to inform SAMG and actions, it is commendable to adopt an integral approach to using PC-based or full-scope severe accident simulators in the SAMG verification and validation processes in the future.*
 - 14) *Alternatively, a computerised SAM support tool (e.g. SAMEX developed by the Korea Atomic Energy Research Institute), which tightly combines a database of pre-analysed severe accident analysis results for a variety of accident scenarios and a severe accident analysis tool with the relevant severe accident simulator, can also help the SAM crew identify quickly various types of diagnostic and prognostic information on plant-specific safety parameters and implement SAMG-specified actions timely.*

8. Recommendations

This report describes the use of analytical simulations to inform severe accident management guidance (SAMG) and actions. Other SAMG verification and validation aspects (see Section 3.2 for details) are not sufficiently covered in this report, such as:

- Expert review of SAMG documentation including technical basis documents
- Evaluation of staff SAMG training requirements and results
- Conduct of plant accident drills/exercises
- Evaluation of SAMG exercises
- Integration into an overall assessment of severe accident management (SAM) effectiveness

Compiling the current practices and providing guidance on those aspects is expected to complement this report and provide a more complete basis on SAMG verification and validation. Therefore, further work on those aspects is strongly recommended.

A comparison of severe accident management guidelines (SAMGs) related to reactors of the same technology (pressurised water reactor, boiling water reactor, CANada Deuterium Uranium reactor, etc.) can also provide interesting lessons and contribute to the validation of these guides. This type of comparison is recommended.

Severe accident research, computer codes and models development, and SAMG refinement, verification and validation are ongoing activities of operators, regulators, engineers and researchers. It is recommended that updates of the relevant sections of this report be made on a regular basis in the future to reflect on the ongoing developments and maintain the validity of the guidance.

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6. Glossary

EDMGs – Extensive Damage Mitigation Guidelines

These are mitigation strategies using readily available resources to maintain or restore core cooling, containment, and spent fuel pool cooling capabilities to cope with the loss of large areas of the facility due to large fires and explosions from any cause, including beyond-design-basis aircraft impacts. (Reference: USNRC, “*The Evolution of Mitigating Measures for Large Fire and Explosions: A Chronological History from September 11, 2001 Through October 7, 2009, (summary and detailed chronology) 2010.*”)

FSGs – Flexible Support Guidelines

These are mitigation strategies, an important component of which is the FLEX programme (Diverse and Flexible Coping Strategies), a set of prepositioned capabilities designed to extend the coping period in the event of an extended alternating current (AC) power loss and other adverse situations such as occurred at the Fukushima Daiichi plant. These capabilities are intended to be used in conjunction with revised SAMG. (Reference: NEI, “*Diverse and Flexible Coping Strategies (FLEX) Implementation Guide,*” (NEI-12-06 Revision 0), Washington, DC, 2012.)

EOPs – Emergency Operating Procedures

These are plant procedures that direct operators' actions necessary to mitigate the consequences of transients and accidents that have caused plant parameters to exceed reactor protection system setpoints or engineered safety feature setpoints, or other established limits. These requirements are provided in 10 CFR Part 50 and in the technical specifications for each plant. (Reference: USNRC, “*Guidelines for the Preparation of Emergency Operating Procedures,*” (NUREG-0899), Washington, DC, 1982.)

SAMGs – Severe Accident Management Guidance or Guidelines

These guidelines are intended to address “beyond-design-basis” situations in which the core has become or is becoming damaged. The goals of the SAMG are to stabilise a degraded core, maintain containment, and minimise the release of the core's fission products. SAMG are much less specific than the EOPs because they cover a wide range of possibilities of the reactor damage state after significant fuel damage occurs. Since in the US SAMGs are voluntary industry initiatives, the US NRC has no specific regulatory control. (Reference: NEI, “*Severe Accident Issue Closure Guidelines,*” (NEI-91-04, Rev. 1), Washington, DC, 1994.) However, in other member countries SAMGs are required and in more or less extent controlled by regulators.

In this report, severe accident management guidance (SAMG) refers to a whole package established for an NPP, which includes all guidelines documents, technical basis documents, enabling instructions, computational aids, etc. Severe accident management guidelines (SAMGs) refer to the guidelines documents such as severe accident guides (SAGs), severe challenge guides (SCGs), etc. SAMGs are also referred to multiple SAMG packages for different NPPs. “SAM actions” are used in a broad meaning including all countermeasures for SAM, such as actions that are documented in SAMG as well as in other procedures and guidelines; “SAMG actions” refer only to the mitigation actions as specified in SAMG.

EME – Emergency Mitigating Equipment

These are equipment and instruments that are not installed as part of the plant design, but are used as an additional provision to mitigate the consequences of an accident including beyond-design-basis accidents (*Reference: CNSC, “Operating Performance, Accident Management”, REGDOC-2.3.2, Version 2, September 2015*). EME also refers to portable or supplementary equipment.

EMEGs – Emergency Mitigating Equipment Guidelines

These guidelines provide instructions for use of EME. The intent of these guidelines is to address beyond-design-basis situations where there is an extended loss of Class IV and III power. Installing the EME pumps and temporary power sources provides fuel cooling (e.g. for CANDU reactors, through water make-up to steam generators, heat transport system, calandria vessel, reactor vault or irradiated fuel bays), containment cooling (e.g. by restoring air cooling units), and some monitoring functions for accident management.