METHODOLOGY FOR CREDITING SEVERE ACCIDENT MANAGEMENT GUIDANCE IN PROBABILISTIC SAFETY ASSESSMENT

Alexander V. Trifanov[1], Sevana Bedrossian[2], Ghulam Khawaja[2], Rob McLean[3], Eliseo M. Chan[3], Derek Mullin[4]

[1] *Kinectrics, Inc., Pickering, Ontario, Canada, alexander.trifanov@gmail.com*
[2] *Ontario Power Generation (OPG), Pickering, Ontario, Canada, sevana.bedrossian@opg.com, ghulam.khawaja@opg.com*
[3] *Bruce Power (BP), Toronto, Ontario, Canada,* rob.mclean@brucepower.com, *eliseo.chan@brucepower.com*
[4] *New Brunswick Power (NBP), Fredericton, New Brunswick, Canada, DMullin@nbpower.com*

Severe Accident Management Guidance (SAMG) is typically not credited in the current Probabilistic Safety Assessments (PSA) because no industry accepted methodology exists to support integration of the SAMG strategies into PSAs. There is increasing interest by utilities and regulators to estimate the potential improvement of plant safety as a result of SAMG implementation and to use PSA for informing SAMG and for personnel training. Therefore, guidance is needed on how the SAMG can be potentially credited in PSAs.

The CANDU Owners Group (COG) initiated a research project to develop a methodology for crediting SAMG in PSA. The methodology developed in this project (Ref. 1) is based on best international practices, experience gained in Canada, and represents a systematic step-by-step process guiding PSA analysts through assessment of plant-specific SAMG for incorporating associated mitigating strategies in PSA. The methodology was tested in a pilot project (Ref. 2) at a Canadian Nuclear Power Plant (NPP) to demonstrate its applicability.

This paper presents the methodology developed for the COG to credit SAMG in PSA and summarizes the results of the methodology application in a pilot project. The methodology addresses the major aspects of crediting SAMG in PSA, such as:

- *Supporting severe accident progression analyses;*
- *Habitability and accessibility of plant locations where mitigating actions are credited;*
- *Survivability of mitigating equipment and instrumentation;*
- *Availability of communication means, portable equipment, special tools and fittings required for establishing credited mitigating strategies;*
- *Human Reliability Analysis (HRA);*
- *Applicability to internal and external hazards; and*
- *Impact of multi-unit severe accident progression.*

I. INTRODUCTION

SAMG is widely implemented at Nuclear Power Plants (NPP) as an additional level of defense-in-depth to improve safety of operating NPPs. However, SAMG is not typically credited in the current PSA, because no industry accepted methodology exists to support integration of the SAMG strategies into PSAs. Thus, PSA does not account for all risk mitigating capabilities available at the plant and provides limited capabilities to support optimization of SAMG strategies.

A methodology was prepared for COG (Ref. 1) to guide PSA analysts in modelling plant-specific SAMG mitigating actions in PSA. The methodology is based on best international practices, experience gained in Canada and represents a systematic step-by-step process to address the major aspects of crediting SAMG in PSA. The methodology was tested in a pilot project (Ref. 2) at a Canadian NPP to demonstrate its applicability.

This paper presents the methodology for incorporating SAMG in PSA prepared for COG and summarizes the results of this methodology application in the pilot project.

II. SUMMARY OF THE METHODOLOGY

II.A. Development of the Methodology

The development of the methodology for crediting SAMG in PSA for COG included the following steps:

1. Review SAMG documentation provided by Canadian utilities and identify generic types of mitigating actions typically used in SAMG.
2. Review the internationally accepted guidance on PSA methods and identify approaches that may be applied to the generic types of SAMG actions determined in item #1.
3. Prepare a methodology document.
4. Test the methodology on a pilot PSA and refine if necessary.

II.B. Specifics of SAMG with Respect to Modelling in PSA

SAMG involves accident mitigating strategies that differ in nature from conventional Emergency Operation Procedures (EOP). This is due to the higher level of uncertainty associated with Beyond Design Basis Accidents (BDBA).

Use of SAMG is required only if the EOPs cannot prevent severe core damage. The interfaces between the SAMG and the EOPs are defined by the SAMG entry and exit conditions. SAMG entry occurs upon indications that severe core damage has occurred or is imminent, and exit takes place when a controlled stable plant state has been achieved. Thus, SAMG cannot impact the Severe Core Damage Frequency, but can reduce the Large Release Frequency (LRF) or other release categories that might be considered in Level 2 PSA.

Once the accident progressed to BDBA and SAMG is entered, the status of the plant is highly uncertain and a significant portion of mitigating equipment has failed. This determines the following specifics of SAMG comparing to EOPs:

1. The command and control is transferred from the control room to the site Emergency Response Organization (ERO).
2. The mitigating strategies are selected based on symptoms rather than diagnostic of a specific accident sequences.
3. Unusual system configurations, recovery of failed equipment, and novel beyond design basis line-ups are considered (i.e., equipment use in SAMG is not constrained by normal design limits and criteria).
4. The goal is to identify as many viable mitigating strategies as possible, thereby increasing the likelihood of stabilizing the plant, rather than relying on a specific set of mitigating strategies defined for Design Basis Accidents.
5. The available station resources may be stretched and possible mitigating strategies are prioritized to ensure efficient coordination and allocation of resources.
6. The SAMG diagnostic tools include the Diagnostic Flow Chart (DFC) and Severe Challenge Status Tree (SCST). The DFC is intended primarily for diagnosis of plant status and early indication of potential challenges to the fission product barriers. The SCST is intended to identify immediate and severe challenges to the containment boundary.
7. A number of severe accident management strategies may have positive and negative consequences. SAMG includes weighing pros. and cons. of the consequences.
8. The survivability of instrumentation and equipment in severe accident conditions may not be ensured. Therefore, diagnoses often rely on alternate means and computational aids.
9. Some plant areas may become uninhabitable due to either harsh environment or radiation fields. This imposes limitations on available mitigating capabilities.
10. On multi-unit sites, the severe accident progression may involve inter-unit impact and the need to manage the resources and priorities on the station level.

The above factors are not within the standard PSA practice typically based on EOPs and design configuration of mitigating systems.

II.C. Overview of the methodology for Crediting SAMG in PSA

The proposed methodology is presented on Figure 1 and represents a systematic step-by-step process guiding PSA analysts through assessment of plant-specific SAMG for incorporating associated mitigating strategies in PSA. The methodology is based on the applicable international and Canadian guidance (mainly Ref. 4, 5, 6, 7, 8, 9, 10, 11) and was adjusted to specifics of the SAMG implementation in Canada.

II.C.1. Key Assumptions

The methodology is based on the following key assumptions that should be tested before application of the methodology:

1. The EOPs include unambiguous cues determining SAMG entrance conditions.
2. The SAMG identifies required monitoring instrumentation and cues, and includes step-by-step or equivalent procedures sufficient in details for an experienced team to establish the credited configuration of mitigating equipment.
3. All personnel that might be involved in accident mitigation following SAMG received adequate training and are qualified for performing all actions prescribed by SAMG.
4. The minimum staff complement required for implementation of SAMG actions has been determined and is maintained available should severe accident occur.
5. The command structure of the SAM team and communication protocols are established.
6. The supporting analyses (e.g., severe accident simulations, equipment survivability assessment, habitability assessment, etc.) have been performed and provide sufficient information for determining:
   - The timeline of the severe accident progression, including the timing of cues defined in the SAMG;
   - The consequences of the modelled mitigating strategies (i.e., the plant state that would be achieved if the strategy is implemented or not implemented);
   - The latest time when a mitigation strategy should be implemented to be effective;
   - The timing of the potential mitigating equipment or instrumentation failure due to the severe accident conditions;
   - The timing when the plant areas that should be accessed by the SAM staff may become uninhabitable.

II.C.2. Process for Incorporating SAMG in PSA for Internal Events

<u>Step 1</u>: Identify SAMG Strategies - Candidates for Modelling in PSA

This step includes a systematic review of the plant SAMG documentation, the internal events PSA, safety analyses, and plant design documentation to identify a preliminary set of SAMG strategies - candidates for modelling in PSA. This selection is preliminary and will be refined using more detailed assessment of various Performance Shaping Factors (PSF) that influence the possibility of incorporating the strategy in PSA.

The SAMG strategies - candidates for modelling in PSA may be selected using the following criteria:

1. Include operator actions that would be started as directed by EOPs prior to transition to SAMG and would continue under SAMG. Some of these actions may not be effective as part of EOP strategies to prevent severe core damage, but may be effective in reducing releases from containment.
2. Include the SAMG strategies that may have positive or negative impact on the release categories considered in PSA (e.g., LRF). For example, containment depressurization using air cooling units may reduce pressure, but also condense the steam, de-inert the containment atmosphere and increase the probability of hydrogen explosion. Both effects should be considered and the strategy should be included. However, the SAMG exit procedures do not impact releases and can be screened out.
3. Screen out the mitigating strategies, for which effectiveness cannot be demonstrated. For example, spraying the release pathways from containment is one of strategies to reduce releases; however, it is difficult to demonstrate that the magnitude would reduce sufficiently to impact the PSA results.
4. Screen out restoration of failed systems unless a specific failure mechanism is defined in the PSA and there is evidence that this failure mechanism can be repaired given severe accident conditions and in time to be effective for accident mitigation.
5. Screen out strategies not defining specific actions, equipment or system configuration.

The result of this task is a list of SAMG strategies - candidates for modelling in PSA. Definition of each strategy should include: the diagnoses tool (e.g., DFC or SCST), the execution instruction, the credited function, systems and their alignment, a representative (or bounding) scenario where the strategy may be applicable, a description how the strategy can impact the accident progression and the plant state that would be achieved once the strategy is implemented. Both positive and negative impacts should be defined.

Step 2: Define Base Human Error Probability (HEP)

The base HEP is used as the starting point of the overall HEP quantification for the credited strategies. It includes both diagnosis and execution components and represents the SAM team performance satisfying the following criteria:

- The SAM team actions are governed by detailed instructions that include all of the information required to effectively perform the task.
- The plant personnel that would be involved in execution of SAMG, should a severe accident occur, have been trained on SAMG in general and specifically on execution of the credited mitigating actions.
- The successful execution of credited actions was demonstrated during drills under nominal conditions.
- The staff complement is sufficient for execution of the credited action given the bounding conditions of the postulated scenario.

If any of the criteria above is not met, the SAMG strategy should not be credited in PSA, because the result of the action may be unknown and the probability of success cannot be defined. If all of the above criteria are met, a base HEP of 1.0E-01 may be assigned consistent with a screening HEP from NUREG-1792 (Ref. 3) or more detailed HRA techniques can be used.

Step 3: Evaluate Feasibility of SAMG Strategies

The base HEP defined in Step 2 assumes that the feasibility of the credited strategy was demonstrated for nominal plant conditions. This step establishes feasibility of the strategy for a specific accident scenario. This includes the following considerations:

Staffing: a specific accident progression may require more staff than in response under nominal conditions.

Timing: for each scenario where the selected candidate strategy is credited, it must be demonstrated that the time available for executing the strategy is equal or exceeds the time required. The calculation of time available and time required should take into account when SAMG entry conditions are met, when the ERO becomes operational, when the strategy entry conditions are met, when ERO provides strategy recommendation to control room staff, time required to implement the selected strategy, time for the strategy to take effect, time when the strategy becomes ineffective (too late to implement).

Habitability and accessibility: assess potential hazards resulting from severe accident conditions that may impact operator actions in a specific accident sequence (e.g., steam, high temperature, fire or flood, high radiation levels, releases of chemical or toxic substances, debris blocking access, etc.)

Communication means: implementation of SAMG strategies requires an effective communication between the ERO, control room staff and field staff. Therefore, availability and reliability of the communication means should be assessed.

Special tools and fittings: if the credited configuration requires special alignment, availability and accessibility of special tools and fittings required to establish this configuration should be assessed.

Survivability of equipment and instrumentation: it should be demonstrated that instrumentation and equipment critical for performing the credited action can survive the severe accident conditions of the accident sequence where the strategy would be credited.

Step 4: Evaluate Stress Factor

A simplified approach based on Canadian experience is proposed in Table I; however, alternative methods may be used as per the current industry practice.

TABLE I. Modification of Base HEP for the Effect of Stress (based on Table 20-16 of (Ref. 4))

Type of SAMG Strategy	Stress Level	Modified
Actions that started as EOP and completed during SAM (the accident already progressed to severe, but is still considered contained)	Moderately High	x 2
Actions initiated under DFC (the accident already progressed to severe, but is still considered contained)	Moderately High	x 2
Actions initiated under SCST (a direct challenge to containment is observed and the threat of large release is present)	Extremely High	x 5

Step 5: Evaluate Potential for Recovery

This step considers credit of self-checking and independent checking. The self-checking is defined as the process of checking that, upon completion, the implementation of the required mitigating strategy has been performed correctly. In order for this error correction to be credited, it must be demonstrated that the time margin is ≥100%. The independent checking is defined as the process of assessment by a qualified member of the team that was not part of the initial equipment alignment. In order for this error correction to be credited, it must be demonstrated that the time margin is ≥200%.

The time margin for this application is determined using Equation (1) and accounts for the time required to:

- Perform the initial diagnosis, determine the strategy, and align the credited equipment.
- Identify if the equipment configuration has not been performed correctly.
- Review and re-perform the equipment alignment steps, when required.
- Determine that the equipment alignment is still incorrect.
- Have an independent checker trouble shoot and direct the crew to re-perform the equipment alignment steps, when required, to correct the error.

$$100\% * [T_{SW} - T_{DIAGNOS} - T_{EXE}] / [T_{DIAGNOS} + T_{EXE}] \qquad (1)$$

Where:

- T_{SW} = the system window, or the time window within which the action must be performed to achieve the goal determined by the credited SAMG strategy. This time is measured from the time the cue setpoint for implementing the SAMG strategy is reached as a result of the accident progression to the time at which the strategy should be implemented.
- $T_{DIAGNOS}$ = the time required for diagnosis of the symptom given the cue and definition of the mitigating strategy or corrective measure.
- T_{EXE} = the time required for execution of the mitigating strategy.

If the self-checking is credited, a high dependence conditions is assumed to exist between the commission of the error and the work to correct it. A probability of 0.5 is assigned to the self-check recovery according to (Ref. 4). If the independent check is credited, a probability of 0.1 is assigned to the independent check recovery according to (Ref. 4).

Step 6: Incorporate the Credited SAMG Strategies in PSA

The SAMG mitigating strategies selected for modelling in PSA rely on specific mitigating equipment, most of which is likely already modelled in the Level 1 or Level 2 PSA. In sequences that progressed to severe core damage, multiple systems might have already failed. Therefore, the PSA model crediting SAMG strategies should explicitly incorporate the system configurations credited in SAMG to account for dependencies on support systems and accident sequences.

The modelling approach depends on specifics of the baseline PSA model and the credited mitigating strategy. However, the following considerations specific to SAMG actions should be taken into account:

1. Typically, instrumentation and communication systems are not explicitly modelled in the PSA assuming that there is a significant redundancy in diagnosis and communication means. This may not be the case in a severe accident where multiple systems might have failed, the assumed redundancy may not be available, and the SAM team will include additional staff (e.g., emergency response and maintenance staff), which will make the effective and timely information exchange critical. Therefore, explicit modelling of instrumentation and communication systems may be required.

2. Modelling of the credited SAMG actions should be based on symptoms and priorities identified in DFC and SCST and not on what the analyst believes would be the best mitigating options. The ERO may not have a complete understanding of the plant status and the trend in the accident progression and will react on symptoms as per the guidance available to them. Therefore, the PSA analyst should review the accident progression predicted by the supporting analysis, assess the timing when specific SAMG setpoints would be reached, take into account whether the critical instrumentation will be available and how unavailability of instrumentation will impact the ERO decision, and determine what strategy the ERO would take given the plant-specific SAMG and accident-specific symptoms. Given that the guidance to perform the action is clear, the resulting strategy should be modelled even if it is not optimum or even is adverse. If the potential ERO decision cannot be determined with a reasonable confidence, the SAMG mitigation should not be credited.

3. The potential long-term impact of SAMG actions on accident progression should be modelled. For example, successful injection into the reactor may stop the core degradation; however, the continuous injection will increase the water level in containment. If operators fail to terminate the injection, the overfilling may fail the containment by hydrostatic pressure and lead to large release. If the injection is successfully terminated, alternative mitigating strategies should be implemented to remove the heat from containment. These alternative means should be modelled on successful isolation of the injection functions.

4. There is uncertainty in the outcome of some of the SAMG mitigating strategies. For example, depending on the rate of water addition to the core, the core geometry and the decay heat, a range of outcomes is possible, from successful quenching and cooling of the debris halting the accident progression to providing a source of steam supporting the oxidation of Zr and generation of hydrogen. It is recommended not modelling mitigating strategies with uncertain outcome unless a supporting analysis provides information on probabilities of various possible consequences. This approach is considered justified, because it is not known whether the ERO will choose to implement the mitigating strategy or not knowing the potential adverse impact and the consequences may be comparable whether the strategy is implemented or not. If the analyst choses to not model such strategies, they may be included in sensitivity studies to assess the relative potential significance of the various outcomes.

Step 7: Assess HEP Dependencies

Once the SAMG strategies are incorporated in the PSA and the preliminary cutsets are generated, the dependencies between HEPs in the same cutset need to be assessed and the combined HEPs need to be adjusted using one of methodologies currently used in the industry. Given that the resulting model is expected to include multiple HFEs in the same accident sequence, it is recommended that the total combined probability of all the HFEs in the same cutset should not be below 1.0E-5 as per the guidance of (Ref. 3).

II.C.3. Considerations for Multi-Unit Sites

For multi-unit sites, the SAMG needs to consider the possibility of the accident occurring concurrently on more than one unit and the inter-unit impact. The guidance followed for an event on a single unit will remain in general valid for each unit, even if a multi-unit event were in progress. However, the accident units may be in different conditions and SAMG strategies will need to be coordinated to ensure that there is no negative impact between activities performed at different units and that inter-unit supply of power, water and instrument air can be applied efficiently for accident mitigation.

The following key severe accident challenges on multi-unit sites should be considered:

1. Impact of activities on non-accident units on the accident unit (e.g., shutdown of non-accident units and placing them in safe shutdown state may be required after a severe accident has been initiated on one unit, but this may reduce the capability of inter-unit supply of water, power or instrument air).
2. Increased demand on station resources due to multi-unit accident progression.
3. Increased demand on communication systems and effectiveness of communication protocols to coordinate activities at multiple units.
4. Concurrent execution of SAMG strategies and prioritization of resources across multiple units.
5. Potential for widespread hazardous radiological conditions.
6. Inter-unit impact through shared systems and services.

II.C.4. Considerations for Internal and External Hazards

In general, the process for incorporating SAMG in PSAs for internal and external hazards should follow the steps described above. However, internal and external hazards are usually associated with common mode impacts on multiple plant systems and structures, as well as additional hazards for operator actions. These factors should be addressed in all steps of the process for incorporating SAMG in PSA. A particular attention should be given to the following elements:

1. *Adjustment of Base HEP*: For some hazards, the value of base HEP may need to be modified to account for specifics of the hazard. For example, the HEP is typically adjusted to account for impact of the magnitude of the hazard, the need to use protective equipment, the spatial interactions in the areas where mitigating actions are performed.

2. *Feasibility of SAMG Strategy*: Hazard-specific impact on staffing, timing, habitability and accessibility with respect to SAMG-related activities and equipment should be considered. For example, high wind and seismic PSAs typically identify the possibility of obstructions on the access paths and in locations of mitigating actions, as well as capabilities and timing for clearing these obstructions. Fire PSA identifies locations impacted by fire and smoke, as well as suppression time.

3. *Fragility of Equipment Credited in SAMG*: If SAMG uses equipment that is not part of the qualified safe shutdown equipment list for a specific hazard, additional fragility assessment for this equipment will be required.

4. *Stress Factor*: Extreme hazard events (e.g., large fires, floods or seismic events) are usually associated with multiple common cause failures of plant equipment and high stress to operators even before the accident progresses to severe core damage. Therefore, the stress factor will require further adjustment.

5. *Credit for Recovery*: The calculation of time margin for credit of recovery in PSAs for internal and external hazards should take into account additional time that might be required for execution of mitigating strategies given the hazard impact (e.g., clearing of obstructions, suppression of fire, recession of flood, decrease of wind speed, etc.)

6. *Impact of Accident Progression on Irradiated Fuel Bay (IFB)*: A severe common mode initiating event that could lead to prolonged station blackout could also affect cooling to the IFB. A seismic event may also challenge the IFB integrity. Uncovering of fuel bundles stored in IFB would result in high radiation fields and would make the site uninhabitable for supporting the mitigating activities on reactors. These factors should be taken into account when modelling severe accident mitigation in PSA.

II.C.5. Uncertainties in the Analysis

The modelling of SAMG in PSA involves significant aleatory and epistemic uncertainties. The common sources of uncertainties associated with the current state-of-knowledge in modelling of severe accidents, SAMG and HRA include:

1. Incomplete understanding of the severe accident progression and consequences of each mitigating strategy.
2. Incomplete understanding of behaviour of the critical SAMG equipment during the severe accident progression.
3. Difficulties in modelling the dynamics of the ERO response, especially in the selection process of the preferred mitigating strategy.
4. Insufficient data for estimating the time required for performing mitigating actions, the probability of human error, and the impact of associated PSFs in the context of the severe accident mitigation.
5. Incomplete modelling (for example, some SAMG strategies may be excluded from modelling in PSA, restoration of failed equipment will likely be excluded, Level 2 PSA model may include only a limited number of representative accident sequences).

The uncertainties applicable to a specific PSA shall be identified and characterized in the PSA report. The uncertainties should be taken into account to determine the modelling approach. For example, if a supporting analysis predicts a very small time margin for implementing a mitigating action, such actions should not be credited given the large uncertainty in the estimate of the severe accident progression timeline. The impact of the uncertainties should be investigated through sensitivity analyses.

III. PILOT PROJECT

The methodology summarized in this paper was applied in a pilot project at a Canadian NPP. All steps of the process where implemented, but only a limited set of strategies that were considered most effective was selected for implementation in the model. The approach was tested and showed a significant reduction of the LRF in sequences where SAMG actions can be credited. However, a number of accident sequences do not allow crediting SAMG or make them ineffective due to phenomenology of the severe accident progression. The insights gained from the study will help to optimize the existing SAMG strategies or developing new more effective strategies.

III. CONCLUSIONS

A methodology for crediting SAMG in PSA was proposed and includes a practical step-by-step guidance for PSA analysts. Although there is currently no industry consensus on the methodology for crediting SAMG in PSA, the proposed approach is based on the existing industry practice for conducting PSA. The methodology is flexible for accommodating its application to specific power plants, includes consideration of internal events, internal and external hazards and multi-unit accident progression.

The methodology was tested in a pilot project and was successful in demonstrating the impact of SAMG on the plant risk and identification of key insights associated with application of SAMG strategies. The pilot project followed the step-by-step approach recommended in the COG methodology (Ref. 1) and used several modelling techniques to demonstrate the flexibility and accommodate the limited scope of the pilot project. Several steps of the process (e.g., quantification of HEP) may apply more detailed methods if desired and considered beneficial.

It is judged that incorporating SAMG in PSA provides the following benefits:

1. A more realistic estimate of LRF by crediting additional mitigating capabilities available at the plant.
2. A demonstration of a lower plant risk.
3. Optimisation and improvement of existing SAMG.
4. A better understanding of the potential negative impacts of SAMG actions depending on specifics of severe accident progression.
5. Development of more effective and efficient new SAMG strategies.
6. A more efficient use of available mitigating equipment and cost-effective selection of design improvements in support of SAMG.

Therefore, further testing of the methodology and a wider implementation by utilities is recommended to refine the methods and to support improvement of plant-specific SAMGs.

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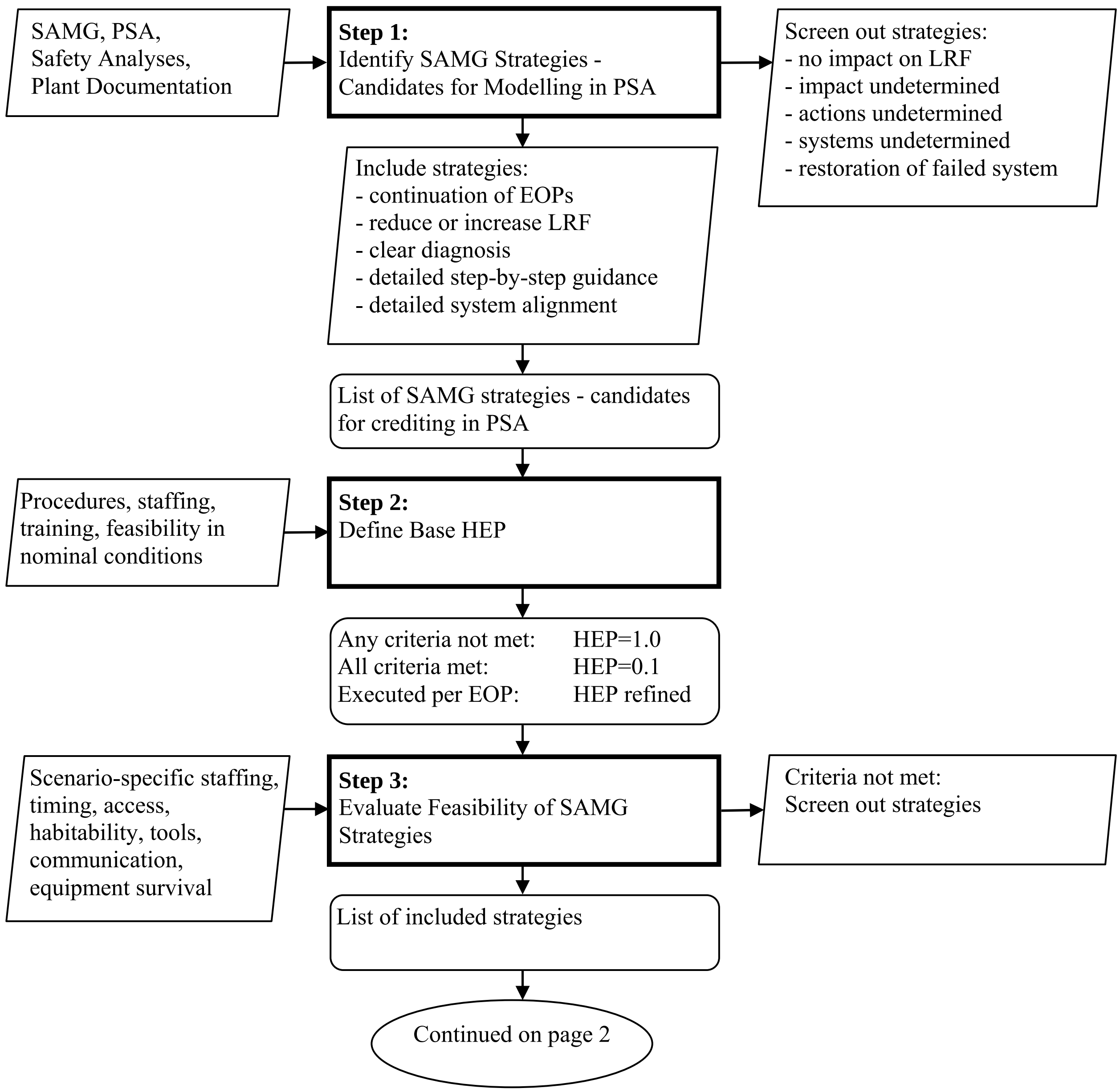

Figure 1: Process for Incorporating SAMG Mitigating Strategies in PSA (page 1)

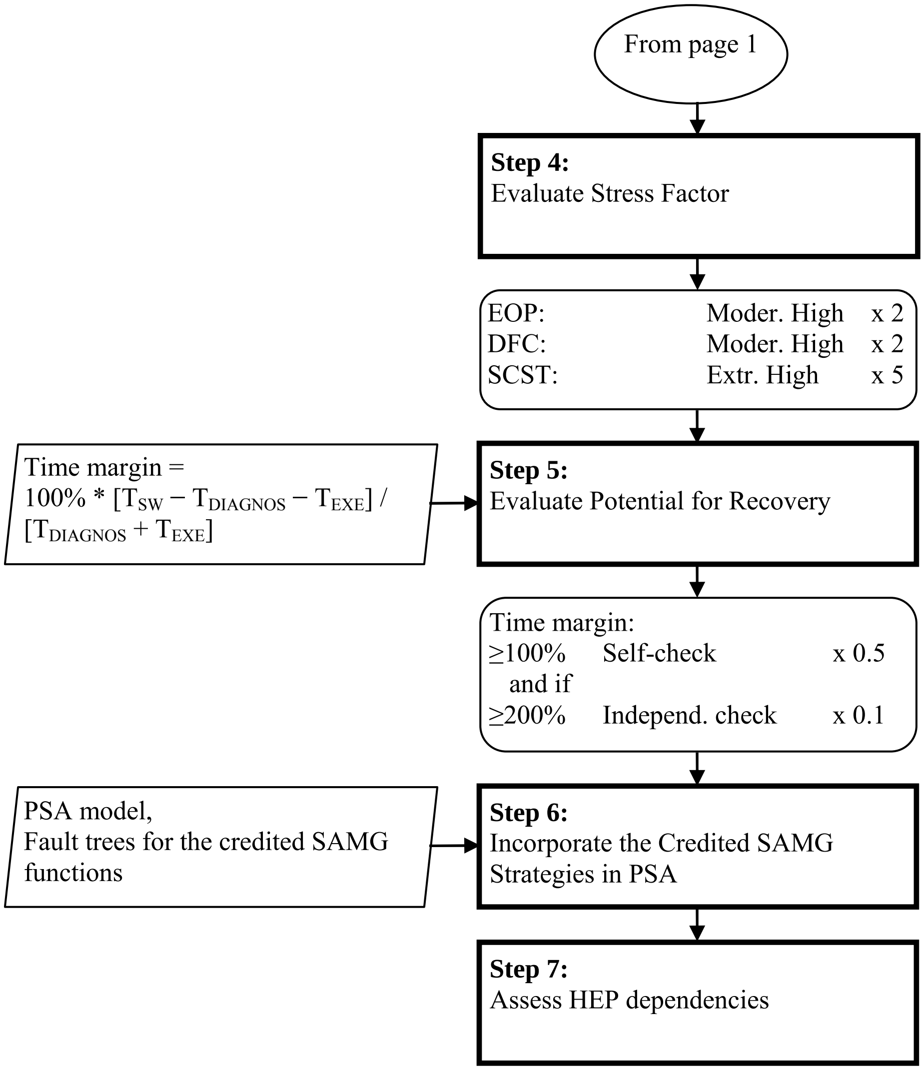

Figure 1: Process for Incorporating SAMG Mitigating Strategies in PSA (page 2)