EUROPEAN
TECHNICAL SAFETY
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TECHNICAL SAFETY ASSESSMENT GUIDE

DETERMINISTIC SEVERE ACCIDENTS ANALYSIS

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FOREWORD

Since the beginning of EUROSAFE initiative (1999), IRSN, GRS and Bel V (former AVN) have pursued the objective to advance the harmonisation of nuclear safety in Europe by comparing their safety assessment methodologies. Based on a long standing experience of more than 40 years, in spite of different national nuclear safety regulatory backgrounds, they have developed practical methods to perform safety assessments that presented sufficient similarities to encourage them to persevere in building a collection of common best practices. The first version of their common Safety Assessment Guide was thus approved in 2004.

The general Safety Assessment Guide (SAG), and its specialized guides, the Technical Safety Assessment Guides (TSAG), have been written by the members of the European Technical Safety Organisations Network with progressive improvements brought by the new members of ETSON.

The SAG provides general principles such as safety assessment objectives or transparency and traceability of the process, and describes the general process for performing the safety assessment of nuclear installations. The goal of this SAG is to set down the harmonized methodology applied by ETSON organisations to ensure a common quality of safety assessment and to develop higher confidence in delivered safety assessments.

The TSAG series consists of specialized guides dedicated to specific technical domains of importance to the safety of nuclear installations. They provide an overview of the available practical knowledge gained by Technical Safety Organisations (TSO) in conducting safety assessments covering these main technical issues (use of operating experience feedback, assessment of human and organisational factors, prevention of severe accidents, probabilistic safety assessment, etc.).

Each guide published by ETSON is updated according to the extension of experience gained as well as to the new requirements in nuclear safety.

The 2012 guides present the common views and practices of ETSON members:

- Bel V - Belgium
- GRS - Germany
- IRSN - France
- VTT - Finland
- UJV Rez - Czech Republic
- LEI - Lithuania
- VUJE - Slovakia
- PSI - Switzerland

With the contribution of ETSON associated members:

- SSTC - Ukraine
- JNES - Japan
- SEC NRS - Russia

CONTENTS

1 SCOPE

The goal of this document is to provide guidance for reviewers of TSOs to check the compliance of submitted safety analysis with safety requirements (or safety objectives) related to severe accidents[1].

This guide mainly applies to deterministic severe accident analysis of Light Water Reactors. The Probabilistic Safety Analysis (PSA) is not covered by this Technical Safety Assessment Guide (TSAG). In spite of this focus, it is up to reviewers to use it properly for another kind of nuclear power plant or spent fuel storage facility[2].

Deterministic severe accident analyses are used/needed, for instance, in the following different areas:

- support of the development of severe accident management (SAM) programmes:
  - for preventive and mitigative SAM measures, often done by hardware modifications (*e.g.*, Passive Autocatalytic Hydrogen Recombiners (PARs), Emergency Filtered Containment Venting System (EFCVS), hydrogen igniters);
  - for SAM guidance (SAMG[3]), especially in the mitigative domain;
- support of PSA level 2;
- support of source term assessment;
- support of equipment qualification programmes.

1 Usually, before utilities perform their analysis, the safety objectives related to the considered problem(s) have been discussed between utilities and the Regulatory Authority and/or its TSO, in order to have a common knowledge of these objectives applied to the particular problem(s) under investigation.

2 Lessons learned from the Fukushima accident are not included in this guide.

3 In this TSAG, the term SAMG is intentionally used for Severe Accident Management Guidance. Such a guidance may be provided by a (single) guide or by a set of guidelines or procedures.

2 BACKGROUND INFORMATION AND CONCEPTS

In addition to the definitions and concepts given in the ETSON General Safety Assessment Guide [1], the following background information and concepts are applicable to severe accidents analyses.

SEVERE ACCIDENT

The definition of a "severe accident" used is based on the IAEA definition (item 4.104 of [2]), nevertheless this definition has been expanded to cover all situations. The definition used by the ETSON members is now the following one:

"Due to multiple failures and/or operator errors, safety systems fail to perform one or more of their safety functions leading to significant core or fuel damage that challenges the integrity of the remaining barriers to prevent the release of radioactive material from the plant."

DETERMINISTIC SEVERE ACCIDENT ANALYSIS

The definition of "deterministic severe accident analysis" is found in the IAEA report on "Severe Accident Management Programmes for Nuclear Power Plants (chapter 3.115 of [3]) and in the IAEA report on "Accident Analyses for Nuclear Power Plants (chapter 5.5 of [4]). The information provided there has been applied for the purpose of this Technical Safety Assessment Guide.

Deterministic analysis of severe accidents are typically performed either for operational plants or for plants at the final stage of design and typically made for the development of Accident Management Programmes. For future plants, such analysis is necessary at the design stage because the requirements for the prevention and mitigation of severe accidents need to be implemented as part of its design.

For severe accidents, specialized codes are used to model the wide range of physical phenomena that occur, such as thermal-hydraulic phenomena, heating and melting of the core, reactor pressure vessel failure, molten-core-concrete interactions, hydrogen generation and combustion, containment performance, and fission product release and behaviour[4]. Either a multi-tiered approach with

4 Typical examples for PWRs.

several interconnected or stand-alone codes, including detailed codes for system analysis and containment analysis, is typically used, or an integral code is used which models the main relevant phenomena. In certain cases, detailed multidimensional codes may be necessary to describe the behaviour of, *e.g.*, the reactor coolant system, molten materials, structures or containment.

Best-estimate assumptions are usually used in the analysis of the overall response of a plant under severe accident conditions, although conservative models are still used to overcome the lack of knowledge in certain areas (recriticality, hydrogen production during reflooding of overheated core, steam explosions, iodine behaviour, etc.). All conservative assumptions taken according to the investigated issue should be clearly identified.

SOURCE TERMS

The definition of the term “source term” is found in the IAEA Safety Glossary [5]. The definition provided there has been modified for the purpose of this Technical Safety Assessment Guide. The definition used by the ETSON members is now the following one:

“The source term is defined as being the amount and isotopic composition of radioactive material released (or postulated to be released) from a nuclear facility. Release conditions, such as sensible heat content or release point elevation, and release kinetics, are also considered as a part of the source term.”

3 REVIEW PROCEDURE

The general safety assessment process is defined in the ETSON General Safety Assessment Guide [1]. The purpose of this TSAG is to describe the review process for severe accident analysis.

The review process should investigate the following items:

1. the identification of the safety objectives to be respected for the safety issue that is investigated;
2. the analysis methodology, the computer codes used and their validation for the safety issue that is investigated;
3. the appropriate use of "key" input data and plant specific details and assumptions in the severe accident analysis;
4. the correctness, completeness and compliance with the state of the art of the severe accident calculations and results;
5. the compliance with the safety objectives applied to the particular problem(s) under investigation.

3.1 Safety objectives

For each safety issue which is investigated in the severe accident analysis, the safety objectives, and the criteria to be respected (if any), should be clearly identified. Moreover, during a review of severe accident analyses, the reviewer should always keep in mind the main safety objectives to maintain the containment integrity and/or to reduce radiological releases.

3.2 Methodology and computer codes used in the analysis

The severe accident analysis may be based on deterministic methods and/or sound engineering judgement or expert advice. In any case, it should be well documented and justified.

The analysis methodology, computer code and models should be suitable for the phenomena investigated. The code should be verified and validated to the extent practical, and be subject to a proper quality assurance programme. This means the code should be applied within its qualification/validation range.

For instance, if local gas concentration in the containment was to be investigated, the code used should be capable of doing that in a trustworthy manner. This could mean that, for certain applications, a lumped parameter code does not give the proper insight, and a CFD-code should be preferred.

Nevertheless, it should be noted that in the severe accident domain, modelling of phenomena is often subject to great uncertainties and the code user should avoid underestimating potential consequences and should maintain adequate safety margins.

3.3 "Key" input data and plant specific details and assumptions

Given the purpose of the analysis and the safety objectives to be met, the reviewers should verify the appropriateness of the use of "key" input data and plant specific details and assumptions and check that the uncertainties, if any, regarding these input data are properly taken into account.

Reviewers should check that the reactor core, reactor cooling system, containment and systems are modelled adequately. These models are particularly significant to the analysis and are influential in determining the course of the accident in the safety assessment. Therefore, all information needed for this purpose should be asked to the analyst and assessed by the reviewers.

The input data used for the analysis should reflect the current status of the plant. If a generic input deck is used, the reviewer should check if its application for the given NPP is acceptable.

Some examples[5] related to these topics are provided below:

- what are the containment characteristics (design pressure, ultimate temperature limits, leak rate, tightness)?
- what are possible radionuclide release paths from the containment through the buildings into the environment including the consideration of plant specific design features?
- does the code adequately take into account the main elements whose chemistry in a NPP containment building may have a significant impact on radioactive releases such as iodine?
- is the expected system behaviour during a severe accident treated adequately?

A summary and outlook of research and development with regard to severe accidents in PWRs is presented in reference [6].

3.4 Calculations and results: correctness, completeness and compliance with the state of the art

Reviewers should check that appropriate methods have been used to select relevant cases for the analyses.

Reviewers should check that justification of the analysis results are based on appropriate code validation and/or practice.

If reviewers use computer codes, it is

5 These examples deal mainly with PWRs.

important that they independently develop the input data deck and select the appropriate modelling for key phenomena. The reviewer should check if the code has been used by an experienced user, familiar with the code characteristics, knowing how to select inputs that have to be provided. The code user should be aware of the code limitations. The reviewers can also check by hand calculations that the results are within the expected boundaries.

As much as possible, some comparisons with other national and international practices, or, if available, any experience feedback, regarding the subject under analysis should be performed. It should include a comparison of the methods used and of the results obtained during other studies carried out for similar facilities or facilities with similar containment systems. However, if performing such comparison, the differences between the facilities need to be recognized very clearly.

Key input data and/or key results that show large uncertainties should be subject of a sensitivity analysis. If the impact of uncertainties is found to be substantial, a proper method to incorporate uncertainties through the analysis should be used.

3.5 Compliance with the safety objectives

For each safety issue which is investigated in the severe accident analysis, the identified safety objectives and the criteria to be respected, if any (see paragraph 3.1) should be checked for compliance, always keeping in mind that the main safety objectives are to maintain the containment integrity and/or to reduce radiological releases.

This check should investigate if there is always sufficient safety margin regarding this main general objective. Moreover, the check should evaluate the plant defence in depth capabilities regarding severe accident.

3.5.1 SAFETY MARGIN

There should always exist sufficient safety margins regarding the main safety objectives to maintain the containment integrity and/or to reduce radiological releases. This item should be checked, especially when so-called "best-estimate" calculation results are provided.

As a matter of fact, reviewers should be aware that:

- the severe accident analyses results are bound to encompass a number of uncertainties. In particular, there is a large extrapolation involved in applying the results of severe accident research to determine the consequences of the severe accident scenarios for prototypic conditions and geometry;
- much of the current capability for severe accident mitigation arises from the behaviour of the containment during a severe accident. Calculations performed relative to the containment behaviour could be limited by the computer codes capability or the nodalisation schemes developed by the analyst;
- for present reactors, the use of some systems outside their qualification range is often foreseen in SAMG. This should be clearly stated in the analysis.

3.5.2 DEFENCE IN DEPTH CAPABILITIES REGARDING SEVERE ACCIDENT

Defence in depth is generally structured in five levels.

For present reactors, level 4, for the control of severe plant conditions, is to include prevention of accident progression and mitigation of the consequences of severe accidents (essentially by means of complementary measures and accident management) (INSAG [7]).

For the next generation of plants, level 4, for the prevention of accident progression, is to consider systematically the wide range of preventive strategies for accident management and to include means to control accidents resulting in severe core damage (INSAG [7]).

The reviewer must check the compliance with the defence in depth concept.

The IAEA document [8] provides a method for assessing the defence in depth capabilities of a nuclear power plant.

3.6 Example of a review process

The general review process steps described above apply for any severe accident analysis.

In practice, review process steps are translated into a questionnaire. An example is given in Appendix for a review of Severe Accident Management Guidance (SAMG).

4 DOCUMENTATION OF REVIEW FINDINGS

As general principles, reviewers should document their review with respect to correctness, completeness and consistency, following the Quality Assurance of their organisation.

The following information should be found in the report with review findings:

- what has been analyzed (scope of the severe accident analysis) and why?
- how was it analyzed (description of the followed methodology: calculation method, hypotheses, assessment criteria, etc.)?
- the comments and questions as a result of the performed review:
  - **a.** the results that are acceptable, and why;
  - **b.** the results that are not acceptable, and why.

Explanation why some points have been rejected or accepted should be as clear and detailed as possible. Items not reviewed or very partially reviewed have to be clearly identified and with due explanation.

The review report should be focused on key aspects related to the safety objectives, keeping in mind that the main purpose of a review is to assess that the plant capacities have been correctly identified, taking into account the recent knowledge.

The final review report should propose recommendations and a follow-up process.

An example of table of content of a suitable review report might be:

a. objective of the severe accident analysis;
b. scope of the review;
c. evaluation of the methodology of the analysis;
d. evaluation of the used codes and main assumptions;
e. evaluation of the results;
f. conclusion: technical comments and findings;
g. references.

5 REFERENCES

- [1] ETSON, General Safety Assessment Guide, (October 2004).
- [2] IAEA, Review and Assessment of Nuclear Facilities by the Regulatory Body, IAEA Safety Standards, Safety Guide GS-G-1.2, Vienna, (2002).
- [3] IAEA, Severe Accident Management Programmes for Nuclear Power Plants, IAEA Safety Standards, Safety Guide NS-G-2.15, Vienna, (2009).
- [4] IAEA, Accident Analysis for Nuclear Power Plants, IAEA Safety Reports Series nº 23, Vienna, (2002).
- [5] IAEA, Safety Glossary - Terminology used in Nuclear Safety and Radiation Protection – 2007 Edition, Vienna, (2007).
- [6] IRSN, Research and development with regard to severe accidents in pressurised water reactors, Summary and Outlook, IRSN report 2007/83, (2007).
- [7] IAEA, Defence in Depth in Nuclear Safety. INSAG Series nº 10, Vienna, (1996).
- [8] IAEA, Assessment of Defence in Depth for Nuclear Power Plants. IAEA Safety Report Series nº 46, Vienna, (2005).
- [9] IAEA, Guidelines for the review of accident management programmes in NPPs, IAEA Services Series nº 9, Vienna, (2003).
- [10] IAEA, Implementation of Accident Management Programmes in NPPs, IAEA Safety Reports Series nº 32, Vienna, (2004).

APPENDIX

REVIEW PROCEDURE FOR A SEVERE ACCIDENT MANAGEMENT GUIDANCE (SAMG)

Although the national practice concerning SAMG is different between countries, an outstanding reference for setting up a review methodology based on international state-of-the-art practices is found in [9]. Since the implementation of SAMG in a nuclear plant should preferably follow main standard steps, internationally proposed by the IAEA [9][10], reviewers of a SAMG should check that all the aspects of these main steps have been properly addressed. The stepwise process to be followed for a SAMG review is summarized below.

1. Selection and definition of a SAMG implementation programme

This includes the basic principles to be adopted, the scope of the programme (*i.e.* will we limit the SAMG to the power states or do we also take into account the shutdown states?), the upgrade policy (*i.e.* will the SAMG be written taking into account the existing plant configuration or are any upgrades foreseen) and compliance with any national regulatory requirements. The main questions to be answered by the SAMG reviewers should be the following:

- has the plant operational state which is the basis of the development of SAMG been well defined?
- have national requirements been addressed?
- is the approach fully symptom based?
- have the entry and exit conditions been defined?
- if applicable, have the transitions between Emergency Operation Procedure (EOP) and SAMG been determined? And, have the existing EOPs been modified to reflect them?

- has the acceptable plant end state configuration (for example a 'controlled stable state') been defined?

2. Assessment of the performed accident analysis used for selection of plant vulnerabilities, for the definition of main strategies and measures and for the development, verification and validation of SAMG and the codes used for this accident analysis

The objective of the review is to assess the completeness and quality of accident analyses performed for severe accidents. It is recommended to verify and validate the developed SAMG by additional analyses, if not already done by the electrical utility, to confirm the effectiveness of the proposed strategies and their potentially negative consequences. The main questions to be answered by the SAMG reviewers should be the following:

SELECTION OF ACCIDENT SEQUENCES

- Have risk significant accidents and/or accident sequence classes been selected?
- Have severe accident phenomena relevant for specific plant been considered in the selection process?

SELECTION OF ANALYTICAL TOOLS AND SET-UP OF INPUT DECK

- Do requirements from the safety authority exist with regard to the application of codes and methods for accident analyses to be performed in the frame of the project? If yes, were they considered?
- Are the codes and methods used capable to adequately model the physical phenomena in question?
- Are the employed codes validated to calculate the specific features of the plant?
- Are the important phenomena and the specific features of the plant adequately modelled by the nodalisation schemes used in accident analyses?
- Are systems dedicated in SAMG adequately modelled in the input deck?

PLANT INFORMATION AND DATA NEEDED FOR ANALYSES

- Is a full description (sometimes called “Engineering Handbook”) available, which describes how the “data base of analyses” has been converted into a representative code input deck?
- Have the representative code input deck and the used “data base of analyses” been independently verified?

PERFORMANCE AND RESULTS OF ACCIDENT ANALYSES APPLIED

- Have analyses been performed on the basis of best-estimate initial and boundary conditions or are conservative assumptions used?
- Have the identified important accident phenomena been considered in the analyses?
- Have vulnerabilities of the plant specific design been identified and reported, and ranked according to their importance?
- Have major challenges to fission products boundaries (integrity of RCS and containment) been identified and reported?

- Do the analyses clearly show the effectiveness of proposed SAMG and their potential negative consequences?
- Were analyses performed to determine that symptom(s) selected for activating measures in key areas of SAMG can be used for the whole range of accident sequences chosen for analyses?

QUALITY ASSURANCE OF ACCIDENT ANALYSES

- Which Quality Assurance procedure has been adopted for the analyses?
- Have the rules defined in the adopted Quality Assurance procedure been followed by the organisations which performed the analyses?
- Has a code user qualification programme been performed and documented?

3. Assessment of plant vulnerabilities and capabilities

A comprehensive set of insights should be obtained on the behaviour of the plant during a severe accident, *i.e.* both the phenomena that will occur plus their timing, as a basis for the later development of accident management strategies. It often includes the effects of various potential strategies as well. The main questions to be answered by the SAMG reviewers should be the following:

- have specific plant vulnerabilities been identified and defined in a systematic way?
- was a suitable and appropriate technical basis (including background documentation and analyses) used to perform the identification of vulnerabilities?
- has the relevance of typical severe accident phenomena for the plant been investigated?
- have the fission product boundaries and the most probable fission product transport paths from the plant into the environment been identified?
- have all relevant plant capabilities to severe accident management been investigated?

4. Development of severe accident management strategies

On the basis of the vulnerability assessment and understanding of accident behaviour, as well as of the plant capabilities to cope with accidents, suitable accident management strategies should be developed. Included in the selection process of possible severe accident strategies is the determination of its negative impacts. The main questions to be answered by the SAMG reviewers should be the following:

- has an appropriate set of criteria or safety objectives been defined in order to allow for grouping of strategies in terms of their urgency, etc.?
- have the strategies been systematically identified, evaluated for potential effectiveness, and evaluated for potential negative impacts?
- has due consideration been taken of the possibility and effects of interactions between different strategies?
- have rules of usage been developed describing among others the selection of priorities, the way the various strategies are implemented, and whether to start already a new strategy before a preceding one is completed?
- has plant specific dedicated systems foreseen for the mitigation of severe

accidents taken into consideration during the development of strategies?

5. Evaluation of plant equipment and instrumentation performance

A major part of accident management could be associated with assessing the availability of equipment and instrumentation and recovering failed equipment. All plant capabilities to fulfil the safety functions could be investigated, including the use of dedicated and non-dedicated systems, unconventional line-ups and temporary connections. Identification of the instrumentation that could be used in the various plant specific strategies determined previously should be reviewed. The main questions to be answered by the SAMG reviewers should be the following:

- are specific (dedicated) systems available or foreseen to mitigate the consequences of severe accidents?
- how is the use of these dedicated systems foreseen in the Accident Management Programme?
- has a systematic review of plant specific systems capabilities (including use of systems for purposes outside their original design basis) been performed, and have the results been specifically reflected in the procedures/guidelines?
- have possible alternative ways to implement a given strategy been identified?
- have the instruments needed been identified in an easily usable way? Is the list comprehensive (systematically identifying requests made in the guidelines)?
- have these instruments been assessed for their likely availability during a severe accident? Is the direction in which instruments may deviate when exposed to harsh environmental conditions known?
- have the conditions under which the instrumentation may be misleading been identified in the guidance?
- have possible alternatives to the preferred instruments been identified and prioritized? Have provisions been made to ensure that instrument indicators are backed up by alternative ones wherever this is feasible?
- have the necessary arrangements been made to ensure that the instrument data are available to the SAMG users?
- have the required Computational Aids been identified based on specific needs, and developed?
- if equipment dedicated to severe accident management has been installed, has it been qualified for the expected accident conditions?

6. Writing of SAMG

During the guideline writing process by utilities, background documents should also have been prepared and integrated into the SAMG package. Reviewers should be careful to address both technical as well as more human orientation key elements. The main questions to be answered by the SAMG reviewers should be the following:

- has guidance been prepared for all involved parts of the organisation (*e.g.* operators, safety engineer(s), Technical Support Center)?
- has user-friendliness of guidelines and procedures been properly addressed, in particular regarding the assessment of availability and capability of plant systems to perform the different strategies?

- have the long-term implications or concerns of implementing the strategies been considered?

- has it been verified that access to equipment even under severe accident conditions will be possible for local actions required by the guidelines?

- has background information been prepared which is plant specific, comprehensive and clear?

7. Verification and validation of SAMG

Reviewers should check the level of SAMG verification and validation performed by utilities. Questions to be answered by the reviewers should be the following:

- was the plant specific SAMG fully and independently reviewed (by utilities), in accordance with the applicable Quality Assurance programme, during their development?

- has an appropriate validation programme been developed and implemented?

- did the scenarios chosen for use in the validation cover a wide range of the procedures/guidelines?

- did the validation test the organisational aspects of severe accident management, especially the roles of the evaluators and decision makers?

- was an appropriate simulation method chosen for validation (simulators, computer simulation, table top exercise, etc.)?

- have the SAMG been tested under conditions that realistically simulate the conditions present during an emergency to include: simulations performance of other response actions, hazardous work conditions, time constraints and stress?

8. Integration between SAMG (*i.e.* Accident Management Programme AMP) and plant emergency arrangement

The purpose of this review task should be to ensure that the Site Emergency Plan has the appropriate criteria and specifications to support the plant specific SAMG implementation. The main questions to be answered by the SAMG reviewers should be the following:

- has the AMP been integrated into the emergency response arrangements? Has the plant emergency arrangements been reviewed and perhaps modified to include new severe accident management functions and responsibilities?

- have the lines of responsibility been clearly defined for evaluators, decision makers and implementers, for all severe accident management functions?

- has the method and responsibility for communications between the different involved parts of the on-site Emergency Response Organisation been defined?

- are the criteria, responsibilities and required time response for activation of the severe accident management team defined and realizable?

9. Staffing and qualifications

It is necessary to ensure that severe accident management staff is appropriately constituted and qualified. The main questions to be answered by the SAMG reviewers should be the following:

- has it been shown that the staff can perform its assigned accident management functions under the conditions anticipated during an emergency (stress, time, heat, radiation, live steam, lifting, climbing, etc.)?
- has it been shown that there will be sufficient equipped staff available to perform the accident management functions in time during an emergency?
- have the functions inside the emergency arrangements organisation been properly described?
- has the decision maker and other people involved in the decision process adequate technical knowledge of severe accident phenomena and accident management?

10. Training needs and performance

Clearly, training of the users of procedures and guidelines and those who interface with them is a key implementation task. The main questions to be answered by the SAMG reviewers should be the following:

- was a training plan developed, in a timely fashion, identifying which staff (individuals and groups) needs training, and at what level? Is a training programme available for each function described in the emergency plans?
- does the training provided focus on correct execution of the emergency plan tasks and, hence, involve knowledge based, skill based and efficiency oriented training?
- are drills and exercises conducted under conditions that realistically simulate the conditions present during an emergency to include: simulations performance of other response actions, hazardous work conditions, time constraints and stress?
- is there a mechanism for feeding back lessons learned from exercises, drills and training into the guidance material, or into the training material itself?

11. SAMG revisions

The last review task consists in verifying whether a mechanism has been put in place which allows the update of accident management guides when new or revised information becomes available.

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