Verification, Validation and Accreditation in the Context of the IMO Second Generation Intact Stability Criteria and the Role of Specific Intended Uses in This Process

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Abstract Verification, Validation and Accreditation (VV&A) are introduced in the context of IMO's Second Generation Intact Stability Criteria (SGISC). IMO's implementation of the SGISC has put in place a multitiered process by which the adequacy of a vessel's stability can be assessed. The application of Verification and Validation (V&V) to the Level 1, Level 2 and Direct Assessment stages of the SGISC are discussed. From the perspective of Level 1 and Level 2 V&V, the user's only responsibility is to verify that the algorithms for assessing vulnerability to stability failure contained in IMO documentation are implemented correctly. The developers of the algorithms for the Level 1 and Level 2 vulnerability assessments need to validate that their algorithms are consistent across a large range of vessel types and sizes. The most stringent criteria of SGISC is Direct Assessment where a vessel is assessed using a physics-based simulation tool. For direct assessment using ship dynamics software for predicting motions in extreme seas, existing well established and documented VV&A processes apply. To be applied to stability assessment, these tools should undergo a formal VV&A to assure that they perform adequately. Before the VV&A can be performed, the problem for which the simulation tool is to be assessed must be defined. This use—the *objectives* of the simulation are defined by the establishment of Specific Intended Uses (SIUs). SIUs are characterized and the way in which they are used are defined.

Keywords Second generation intact stability criteria · Verification, Validation and Accreditation (VV&A) · Specific intended uses (SIU)

1 Introduction

For most vessels, the general intact stability criteria is based on the work of [21]. Today, the intact stability criteria for commercial vessels is provided by the Inter-

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K. J. Spyrou et al. (eds.), *Contemporary Ideas on Ship Stability*, Fluid Mechanics and Its Applications 134, https://doi.org/10.1007/978-3-031-16329-6_13

national Code on Intact Stability, the 2008 IS Code (MSC 85/26/Add.1[1]). Similar criteria for naval vessels are provided by [26] and codified in the NATO Naval Ship Code [18, 19] and by a US Navy Design Data Sheet [25]. These criteria are prescriptive—that is they are a set of criteria, based on empirical data, which are assumed to ensure that a vessel meeting the criteria will have adequate intact stability (static and to a limited extent dynamic stability). The criteria are also binary, in that a vessel either meets the criteria or it does not. The history of development and the background of the IMO criteria are described by [16]; a summary of the origin of these criteria is also available in Chap. 3 of the Explanatory Notes to the International Code on Intact Stability (MSC.1/Circ.1281).

Beginning in the early 2000s efforts were initiated to develop performance based stability criteria for commercial vessels with the re-establishment of the intact-stability working group by IMO's Subcommittee on Stability and Load Lines and on Fishing Vessels Safety (SLF) (cf. [9, 10]).[2] Over time, the terminology to describe the new intact stability criteria evolved from "Performance Based" to "Next Generation" to "Second Generation"—the terminology in use today. This entire evolution is described in the introduction to [20].

The SLF Working Group on intact Stability decided that the Second Generation Intact Stability Criteria (SGISC) should be performance-based and address three modes of stability failure (SLF 48/21, paragraph 4.18):

- *Restoring arm variation* problems, such as parametric roll and pure loss of stability;
- *Stability under dead ship condition*, as defined by SOLAS regulation II-1/3-8; and
- *Maneuvering related problems in waves*, such as surf-riding and broaching-to.

Ultimately, a fourth mode of stability failure was added:

- *Excessive accelerations*.

The criteria and processes were first discussed in [4]. The state-of-the-art in the assessment of vulnerability is presented in detail in [20] and further summarized in [23]

The deliberations of the Working Group on intact Stability led to the formulation of the framework for the SGSIC, which is described in SLF 50/4/4 and was discussed at the 50th session of SLF in May 2007. The key elements of this framework were the distinction between parametric criteria (the 2008 IS Code) and performance-based criteria, and between probabilistic and deterministic criteria. Special attention was paid to probabilistic criteria; the existence of the *problem of rarity* was recognized for the first time and a definition was offered. Also, due to the rarity of stability failures, the evaluation of the probability of failure with numerical tools was recognized as a significant challenge.

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[1] References to IMO documents such as "MSC 85/26/Add.1" appear in the list of references with an "IMO" prefix, i.e., as: IMO MSC 85/26/Add.1. As there is no ambiguity in the names of the IMO citations, the year will be omitted from the citations.

[2] Due to a reorganization of IMO in the early 2010s,s, functions of SLF were transferred to the Subcommittee on Design and Construction (SDC); since 2013 SDC has been developing the second-generation intact stability criteria.

The SGISC are based on a three-tiered assessment approach: for a given ship design, each stability-failure mode is evaluated using two levels of vulnerability assessment in the first and second tiers, respectively. A vessel that fails to comply with the criteria of the first and second tiers must progress to the third tier where it is examined by means of a direct assessment procedure based on tools and methodologies corresponding to the best state-of-the-art physics-based prediction methods in the field of ship-stability failure prediction.

If decisions regarding the adequacy of a vessel stability-wise, are going to be made based on the predictions of a Modeling and Simulation (M&S) tool, there must be a reasonable assurance that the tool provides acceptably accurate results. The process by which a tool may be determined to be sufficiently accurate is known as Verification, Validation and Accreditation (VV&A).

As the SGISC are more extensive (deal with multiple stability failure modes) and more complex than the older prescriptive approach to stability, it will be necessary to ensure that the algorithms supporting the assessment are consistent and implemented correctly. It is the objective of this paper to provide some insights on these latter two issues.

In the process leading to accreditation by a Flag Administration, VV&A must be a formal process with structure that is prescribed. This structure includes the identification of an Accreditation Authority and the establishment of accreditation panels; and is described in [23]. Additionally, the process of accreditation requires Specific Intended Uses (SIUs)—the objectives against which accreditation occurs.

2 IMO Second Generation Intact Stability Criteria

The SGISC are based on a three-tiered assessment approach: for a given ship design and loading condition, each stability-failure mode is evaluated using the first two tiers of vulnerability assessment, as necessary. The criteria for the first tier is the Level 1 criteria and that of the second tier, the Level 2 criteria—these two tiers of vulnerability assessment criteria are characterized by different levels of accuracy and computational effort, with Level 1 being simpler and more conservative than Level 2.

A ship, which fails to comply with the Level 1 criteria is assessed using the Level 2 criteria. In a case of unacceptable results at the second tier, the vessel must then proceed to the third tier, and be examined by means of a direct assessment procedure based on tools and methodologies corresponding to the best state-of-the-art prediction methods in the field of ship-capsizing prediction. This third-tier methodology should capture the physics of capsizing as practically possible.

If a design does not meet the stability requirements after direct assessment, then the only choices are: abandoning that specific loading condition, changing the design, operational measures or operational guidance. In reality, at any stage of the assessment the designer, the builder or the owner may choose to proceed to the application of any one of these four options if he wishes. This process is illustrated in Fig. 1.

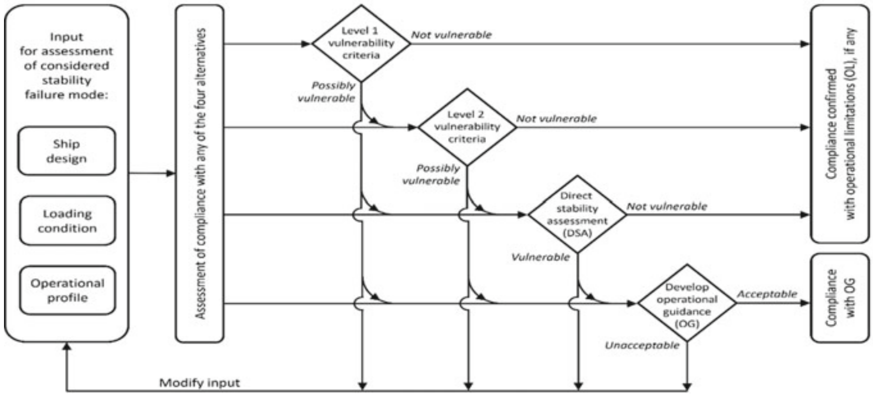

Fig. 1 High-level flow chart for the IMO 2nd generation intact stability criteria (from: MSC.1/Circ.1627)

The three levels of assessment are intended to be of increasing complexity with the Level 1 assessment being a simple "back of the envelope" calculation that should be simple enough that it can be completed for all stability failure modes in a day. The Level 2 assessment is more complex and might require as much as a week's effort to assess all stability failure modes, and require the use of computational algorithm implemented in a program such as Excel or MathCad—here after referred to as a spreadsheet. The third level direct assessment will require the use of serious computing resources and could take a month or more's effort.

The specific formulations for the SGISC were released for the trial use in December 2020 as MSC.1/Circ.1627, Interim Guidelines on The Second Generation Intact Stability Criteria. MSC.1/Circ.1627 consists of four main sections: General, Guidelines on vulnerability criteria, Guidelines for direct stability failure assessment and Guidelines for operational measures. The Guidelines on vulnerability criteria section defines the Level 1 and Level 2 vulnerability criteria. The explanatory notes for MSC.1/Circ.1627 are still under development by the Intact Stability Correspondence Group (ISCG)[3].

3 Verification, Validation and Accreditation

Software that is being used for engineering computations, upon which design decisions will be based needs to be correct. The processes by which software is assessed as to its correctness and being adequate for the job is called verification, validation and accreditation (VV&A)—verification assesses correctness and validation assesses the degree to which it is adequate for the task, accreditation assures that the software

[3] MSC.1/Circ.1652, to be published in 2023.

is adequate for the specific use that is specified. As stated by [24], verification is "solving the equations right" and validation is "solving the right equations." People have said that accreditation is simply "validation with criteria."

Papers and reports by [1–3, 5–8, 11, 17, 22, 23] provide different, although consistent, formal definitions of VV&A. The U.S. DoD definitions for these terms are provided below, each followed by a practical commentary relevant to computational tools for predicting dynamic stability.

1. *Verification*—the process of determining that a model or simulation implementation accurately represents the developer's conceptual description and specification, *i.e.*, does the code accurately implement the theory that is proposed to model the problem at hand?
2. *Validation*—the process of determining the degree to which a model or simulation is an accurate representation of the real world from the perspective of the intended uses of the model or simulation, *i.e.*, does the theory and the code that implements the theory accurately model the relevant physical problem of interest?
3. *Accreditation*—the official determination that an model or simulation, …is acceptable for use for a specific purpose, *i.e.*, is the theory and the code that implements it adequate for modeling the physics relevant to a specific platform? In other words, are the theory and code relevant to the type of vessel and failure mode for which it is being accredited?

As the Level 1 and Level 2 vulnerability criteria are specified by IMO, the code for these assessments only need to go through the verification and validation (V&V) processes to ensure that the code is correct. The direct assessment software, not being specified in any detail needs to undergo the entire VV&A process.

4 V&V from the User's Perspective

For the SGISC, the question of V&V has to cover a broad range of computations/computational tools—from the "back of an envelope" assessment to sophisticated ship dynamics computational tools. As each of the levels of assessment has its own issues, they will be discussed separately, beginning with Direct Assessment, where the computational tools that are traditionally put through the V&V process would be employed.

4.1 Direct Assessment

As just stated, the hydrodynamic computational tools for predicting ship dynamics are the types of software for which the V&V processes have been developed. So while these are the most complex software tools that must be put through the V&V

process, and the tools for which the most effort will have to be expended, they are the tools for which the process is the most mature. As stated previously, there is an abundance of literature on the subject of formal V&V of software (cf. [1, 2, 5–8]. [23] provide a survey of the formal V&V process tailored for the ship stability community.

From the users perspective, it is unlikely that a user will be developing a computational tool for assessing dynamic stability performance in extreme seas; the user will most likely be employing software developed by a third party. Thus, the user will not be responsible for verification of the software, he will have to assume that the software vender has performed that function, and the user will only be responsible for performing validation to assure that the software tool is adequate for predicting the stability failure mode(s) of concern. The Flag Administration, responsible for the vessel being assessed, should have defined the process for formal validation.

4.2 Level 2 Criteria

For Level 2, the SGISC will explicitly provide the user with the algorithm for use in assessing the vulnerability of a ship to each particular stability failure mode. Thus, there should be no requirement for the user to perform validation of a spreadsheet that is used to perform the vulnerability calculations. However, it will be necessary to perform verification to insure that the calculations are performed correctly.

The issue then becomes one of how best to perform this verification. It would appear that the ideal situation would be to have a series of benchmark cases for each stability failure mode. For each failure mode there would be pairs of cases, one of the pairs being a case that passes the vulnerability test for that mode and one that fails the vulnerability test. For Level 2 algorithms where there are binary decision points within the algorithm, there should be a pair of benchmark cases that will test each branch of the decision tree.

Under these conditions, the user would be required to enter each pair of benchmark data into his spreadsheet and show that the results of each case agree with the expected answer within a specified accuracy, say 2-percent. When a user has performed and passed this level of validation for all five stability failure modes, he could be "certified" by a Flag Administration to use his spreadsheet to assess the vulnerability of his design to stability failure.

4.3 Level 1 Criteria

In principle, the Level 1 V&V should be similar in complexity to the Level 2 problem and have the same approach. However, there is one complication at Level 1. Level 1 vulnerability assessment has been characterized as an assessment that can be carried out on the "back of an envelope" using a hand calculator, but this opens the Level 1 assessment up to a lack of repeatability due to simple calculation errors—the *details* of the Level 1 calculations need to be recorded. Therefore, it is proposed that, even at Level 1, it be required that the vulnerability assessment for each mode of stability failure be implemented in a spreadsheet. This will vastly reduce the possibility of inadvertent errors due to "hitting the wrong key" on a calculator, and will greatly facilitate verification using the same benchmarking process proposed for Level 2.

5 V&V from the Criteria Developer's Perspective

The developers of the Level 1 and Level 2 intact stability vulnerability criteria are not developing software, so they do not have any responsibility for V&V in the traditional sense. However, they do have responsibility for ensuring that the algorithms that they are developing are consistent—this is a validation function.

What is meant by consistency of algorithms? If the Level 1 and Level 2 algorithms are developed from the same theoretical basis, then the validation can be performed largely at the theory/algorithm basis, but if not, then extensive computational testing is required. A hypothetical example of a theoretically consistent Level 1 and Level 2 vulnerability assessment would be where the Mathieu equation is used to evaluate the sensitivity to parametric roll, with the Level 1 algorithm using the Mathieu equation without the roll damping term and the Level 2 algorithm using the Mathieu equation with a roll damping term.

In the absence of such a consistent theoretical basis, the validation of the Level 1 and Level 2 algorithms consists of two steps. First, the algorithms must be rational, that is they should not be based on the use of logically inconsistent information; and second, they must undergo an extensive computational consistency check. To give a ludicrous example of a rationality check, a stability failure algorithm based, among other things, on the distance from the earth to the moon would be highly suspect. Someone other than the developer of the algorithm should conduct the *rationality* step of the validation.

The second step, the computational validation, will involve evaluating a large number of vessels of various types and sizes using both the Level 1 and Level 2 algorithms for each mode of stability failure. The metric here is two-fold, first that a vessel in a given loading condition that passes the Level 2 vulnerability test should not fail the Level 1 vulnerability check. And secondly, for those vessels that pass both the Level 1 and Level 2 vulnerability check, the margin at Level 2 should not be smaller than the margin at Level 1—if a vessel passes the Level 1 check by a large margin, it should not pass the Level 2 check by only a small margin, this is admittedly somewhat subjective.

6 Role of SIUs in Accreditation

As described above, accreditation is the process by which a computational tool is certified as being sufficiently accurate and thus acceptable for use in a particular case for a particular vessel or class of vessels. In the IMO SGISC context, this would be a vessel of a particular size and proportions, which will have a particular mode of operation. In practice this would also be tied to a particular mode of stability failure and would be defined as a particular SIU.

Specific Intended Uses (SIUs) are the statements that define the scope of the problem or simulation that is to be modeled, and for which the M&S will be accredited. In the context of direct assessment under SGISC, this will need to include a definition of the type of vessel for which the M&S tool is to be accredited—accreditation for small fishing vessels may well not apply to a container carrier; as well as the mode of stability failure that is anticipated to be an issue. There can, and in fact would likely be multiple SIUs for the same VV&A activity.

6.1 Example of an SIU

As stated earlier, the SIU effectively defines the objective of the accreditation. As such, the SIU needs to answer the questions "what" and "why." The "what" part of the answer will in the case of accreditation have two parts, one part pertaining to the type of vessel, and the other pertaining to the mode of stability failure. An example of this would be the accreditation of a code for predicting parametric roll of a container carrier—container carrier would be the type of vessel and parametric roll would be the mode of stability failure.

The "why" question relates to the way in which the predictions from the code will be used. Will the code be used to determine whether a vessel is susceptible to parametric roll in head seas at 24 kt in a particular sea state, or will it be used to derive a speed polar plots for susceptibility to parametric roll in a series of sea states. The answer to the "why" question serves to define the scope of the effort required in the accreditation process.

To clarify, an example of a SIU is: "The XYZ simulation tool will be used to generate operator guidance polar plots for all applicable speeds and headings against pure loss of stability for RO/PAX vessels in the 11,000–13,000 t displacement range, lengths of 130–150 m, and with beam-to-draft ratios of 4.5 to 5.5. These polar plots will enable the vessel operators to avoid situations where pure loss of stability could be an intact stability issue. The information used to generate the operational guidance polar plots will be developed using numerical data generated by the XYZ simulation tool."

In the example SIU, the answers to the "what" question are RO/PAX vessels in a particular size range with the stability failure mode being pure loss of stability. The answer to the "why" question is to generate operational guidance polar plots for all applicable speeds and headings.

6.2 Requirements Flow-Down Table

The answers to the "what" and "why" questions within the SIU are used to determine what needs to be characterized and analyzed from the perspective of the V&V process. This is accomplished by the development of a Requirements Flow-Down Table. In the Requirements Flow-Down Table, each SIU is decomposed in to several high level requirements (HLRs), which characterize important aspects of the SIU. The HLRs are each further mapped into several detailed-functional requirements (DFRs). A comparison metric and an acceptance criterion are identified for each DFR. Additional clarification is provided by the definition of the comparison metrics and their associated acceptance criteria. HLRs reflect the technical specifications provided by SME-opinion. DFRs provide additional specifications as necessary to more fully-describe each HLR. Requirements Flow-Down Tables are useful tools in high-level assessment of the appropriateness of the proposed accreditation criteria as well as required components of the Accreditation Plan [8].

An example of a Requirements Flow-Down Table, Table 1, is provided for the example SIU given above.

7 Summary

With the advent of the Second Generation Intact Stability Criteria, IMO has initiated a three-tier performance-based stability assessment process for unconventional hulls with a risk of intact stability failure. If the design fails the first and second level tests, it then progresses to the third tier and direct assessment, which requires an accredited physics-based simulation tool.

From the perspective of Level 1 and Level 2 verification and validation, the user's only responsibility is to verify that the algorithms for assessing vulnerability to stability failure contained in IMO documentation are implemented correctly. To facilitate this, there needs to be a comprehensive set of benchmark cases that both meet and fail to meet the vulnerability criteria, covering each of the stability failure modes. For direct assessment using ship dynamics software for predicting motions in extreme seas, the well-established and documented V&V process of [1, 2, 5–8, 11], *etc.*. apply. The developer of the algorithms for the Level 1 and Level 2 vulnerability assessments need to validate that their algorithms are consistent across a large range of vessel types and sizes.

The one significant note is that even though, in general, the Level 1 vulnerability assessment can be performed "on the back of an envelope" using a hand calculator, those calculations need to be performed using a spreadsheet program on a personal computer or reliable and consistent verification will be virtually impossible.

Accreditation requires that a set of Specific Intended Uses (SIUs) defining the objectives of the accreditation, be defined. These SIUs must define what the M&S is to be accredited for (type of vessel and mode of stability failure) and why (the product to be produced by the M&S).

Table 1 Example requirements flow-down table

High level requirements	Detailed functional requirement	Comparison metric	Acceptance criteria
HLR 1.a Simulation must demonstrate good correlation to model data for ship responses to elemental tests to suggest that underlying physics are sound.	DFR 1.a.1 Simulation must demonstrate the ability to successfully predict critical motion values in a large number of Quantitative Accreditation conditions for which model test data is available for comparison	CM 1.a.1 Check-list of quantifiable metrics defining "reasonable" correlation for elemental tests used to inform SME opinion	AC 1.a ARP will vote using SME opinion informed by elemental test comparisons whether to assess subsequent acceptance criteria
	DFR 1.a.2 Collective SME judgment shall ultimately decide whether or not this requirement is met (regardless of the code's ability to meet the suggested quantifiable metrics).	CM 1.a.2 SME opinion/judgment	
HLR 1.b The simulation and model-scale data must show consistently good correlation ranging from the more simple conditions to the more complex conditions. Good correlation must be demonstrated for the range of operational, environmental, and loading conditions defined in the Quantitative Accreditation scope for which comparison model data are available.	DFR 1.b.1 Parameters which characterize the ship's operating condition relative to the seaway, and identify the corresponding critical motion, must be assessed.	CM 1.b.1 Mean values, μ, of achieved speed and heading	AC 1.b.1 Differences between mean achieved speed and mean achieved heading for each validation condition must be less than specified amounts
	DFR 1.b.2 All comparisons must take into account all known sources of uncertainty (sampling, instrument, condition, etc.)	CM 1.b.2 90% uncertainty intervals on the each parameter (model and simulation)	AC 1.b.2 The 90% confidence intervals on each parameter value (σ and A90%) for a given motion and condition must overlap in order to suggest that the underlying populations (model and simulation) may be the same
	DFR 1.b.3 Parameters that are used to define Quantitative Accreditation polar plots risk values and lifetime risk calculation must be assessed. If direct validation of these quantities is not achievable, a sufficient substitute quantity shall instead be assessed. (rare motion metrics)	CM 1.b.3 The 90th percentile of peak amplitudes, A90%, of motions (in lieu of exceedance rates of physical limit thresholds which are not expected to be available for validation)	
	DFR 1.b.4 Parameters that are used to evaluate the quantitative accreditation system health must be assessed. (non-rare motion metrics)	CM 1.b.4 Mean standard deviation, σ, of motions	

(continued)

Table 1 (continued)

High level requirements	Detailed functional requirement	Comparison metric	Acceptance criteria
High level requirements	**Detailed functional requirement**	**Comparison metric**	**Acceptance criteria**
HLR 1.c Necessary accuracy of the simulation shall be influenced by an appropriate balance between technical excellence and judiciousness	DFR 1.c Thoughtful engineering judgment shall be applied in the determination of permissible differences between simulation and model test results	CM 1.c Margin applied to observed sample parameter values (defined in CM 1.b.2 and CM 1.b.3)	AC 1.c The observed values of compared sampled parameters may be deemed acceptable if the difference between the values is less than a specified amount (margin)
HLR 1.d The safety of the ship and sailor must be prioritized and reflected in the criteria established for validation	DFR 1.d.1 Reasonable conservatism on the part of the simulation solution should be endorsed to promote the overall safety of the sailor.	CM 1.d.1 Margin applied to observed sample parameter values (defined in CM 1.b.2 and CM 1.b.3)	AC 1.d.1 The margin allowed by AC 1.c shall be increased by 50% in the case of over-prediction on the part of the simulation to allow for additional conservatism on the part of the simulation. (additional conservative margin)
	DFR 1.d.2 Determination of simulation tool success must only be reached using reasonably high-fidelity validation data sets	CM 1.d.2 Combined uncertainty in the comparison, calculated as a function of the 90% uncertainty intervals (CM 1.b.2) on both data sets, model and simulation	AC 1.d.2 Successful validation comparisons for both rare and non-rare motions (σ and A90%) may only be accepted if the combined uncertainty in both data sets is sufficiently small
HLR 1.e Simulation must be deemed usable for conditions within the current scope of the quantitative accreditation for which comparison model test data is not available	DFR 1.e.1 Simulation must demonstrate the ability to successfully produce critical motion values in a large number of quantitative accreditation conditions for which model test data is available for comparison	CM 1.e.1 Number of conditions which successfully pass the following criteria: AC.1.b.1 through AC 1.d	AC 1.e 70% of quantitative accreditation conditions for which model data are available for comparison must pass criteria (AC 1.a through AC 1.d) for 100% of critical motion parameter values. (rare and non-rare motion assessments calculated independently)

Additionally, the Requirements Flow-Down Table which is used to define comparison metrics and acceptance criteria based on the SIUs are described, and an example is provided.

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