U.S. Department
of Transportation
Federal Aviation
Administration

Advisory Circular

Subject: Describing Flight Safety Analysis Methods	Date: 09-20-2024 Initiated By: AST-1	AC No: 450.115-2

This Advisory Circular (AC) provides guidance for documenting the methods used in a flight safety analysis in accordance with title 14 of the Code of Federal Regulations (14 CFR) § 450.115(c). This guidance is not legally binding in its own right and will not be relied upon by the Federal Aviation Administration (FAA) as a separate basis for affirmative enforcement action or other administrative penalty. Conformity with the guidance is voluntary only and nonconformity will not affect rights and obligations under existing statutes and regulations.

If you have suggestions for improving this AC, you may use the Advisory Circular Feedback form at the end of this AC.

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1 PURPOSE.

This Advisory Circular (AC) provides guidance for documenting and submitting a description of the methods used in a Flight Safety Analysis (FSA) in accordance with title 14 of the Code of Federal Regulations (14 CFR) § 450.115(c). Engineers developing and documenting engineering methods should use this AC to understand the requirements in § 450.115(c). Regulatory compliance leads should use this AC to ensure submissions thoroughly respond to requirements. FAA evaluators should use this AC as a guide to evaluate submissions. All readers should have a general understanding of flight safety analysis and of standards for scientific and engineering documentation.

1.1 Level of Imperatives.

This AC presents one, but not the only, acceptable means of compliance with the associated regulatory requirements. The FAA will consider other means of compliance that an applicant may elect to present. In addition, an operator may tailor the provisions of this AC to meet its unique needs, provided the changes are accepted as a means of compliance by the FAA. Throughout this document, the word “must” characterize statements that directly follow from regulatory text and therefore reflect regulatory mandates. The word “should” describe a requirement if electing to use this means of compliance; variation from these requirements is possible but must satisfy the regulation to constitute an alternative means of compliance. The word “may” describe variations or alternatives allowed within the accepted means of compliance set forth in this AC.

2 APPLICABILITY.

2.1 The guidance in this AC is for launch and reentry vehicle operators required to comply with 14 CFR part 450. The guidance in this AC applies to operators seeking a launch or reentry vehicle operator license, a licensed operator seeking to renew or modify an existing vehicle operator license, and FAA commercial space transportation evaluators.

2.2 The material in this AC is advisory in nature and does not constitute a regulation. This guidance is not legally binding in its own right, and the FAA will not rely upon this guidance as a separate basis for affirmative enforcement action or other administrative penalty. Conformity with this guidance document (as distinct from existing statutes and regulations) is voluntary only, and nonconformity will not affect rights and obligations under existing statutes and regulations.

2.3 The material in this AC does not change or create any additional regulatory requirements, nor does it authorize changes to, or deviations from, existing regulatory requirements.

3 APPLICABLE REGULATIONS AND RELATED DOCUMENTS.

3.1 Applicable United States Code (U.S.C.) Statute.

- Title 51 U.S.C. Subtitle V, Chapter 509, Commercial Space Launch Activities.

3.2 Related Code of Federal Regulations.

The following Title 14 CFR regulations should be accounted for when showing compliance with 14 CFR § 450.115(c). The full text of these regulations can be downloaded from the U.S. Government Printing Office e-CFR. A paper copy can be ordered from the Government Printing Office, Superintendent of Documents, Attn: New Orders, P.O. Box 371954, Pittsburgh, PA, 15250-7954.

- Section 401.7, *Definitions.*
- Section 450.35, *Means of Compliance.*
- Section 450.45, *Safety Review and Approval.*
- Section 450.101, *Safety Criteria.*
- Section 450.108, *Flight Abort.*
- Section 450.113, *Flight Safety Analysis Requirements—Scope.*
- Section 450.117, *Trajectory Analysis for Normal Flight.*
- Section 450.119, *Trajectory Analysis for Malfunction Flight.*
- Section 450.121, *Debris analysis.*
- Section 450.123, *Population Exposure Analysis.*
- Section 450.131, *Probability of Failure Analysis.*
- Section 450.133, *Flight Hazard Area Analysis.*
- Section 450.135, *Debris Risk Analysis.*
- Section 450.137, *Far-field Overpressure Blast Effects Analysis.*
- Section 450.139, *Toxic Hazards for Flight.*

3.3 Related FAA Advisory Circulars.

FAA Advisory Circulars are available through the FAA website, Advisory Circulars (ACs) – AST. The following Advisory Circulars contain information about the specific content of a methods descriptions in flight safety analysis:

- AC 413.13-1, *Guidance on Submitting a Complete Enough and Complete Application for a Vehicle Operator License*, dated December 18, 2023.
- AC 450.101-1B, *High Consequence Event Protection*, dated May 3, 2024.

- AC 450.108-1, *Using Flight Abort Rule as a Hazard Control Strategy*, dated July 7, 2027.
- AC 450.115-1B, *High Fidelity Flight Safety Analysis*, dated August 2, 2024.
- AC 450.117-1, *Normal Trajectory Analysis for Normal Flight*, dated August 19, 2021.
- AC 450.123-1, *Population Exposure Analysis*, dated October 12, 2022.
- AC 450.141-1A, *Computing System Safety*, dated August 16, 2021.

Note: Additional ACs are planned for other flight safety analysis sections of the regulation.

3.4 **Additional References Related to Rigor of Flight Safety Analysis Methodology.**

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3. Department of Defense. *Department of Defense Standard Practice: Documentation of Verification, Validation, and Accreditation (VV&A) for Model and Simulations*. MIL-STD-3022 Change 1. 5 April 2012. https://quicksearch.dla.mil/qsDocDetails.aspx?ident_number=275961.
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5. National Aeronautics and Space Administration (NASA). *NASA Technical Standard, NASA-STD-7009B, Standard for Models and Simulations*, March 2024 https://standards.nasa.gov/standard/NASA/NASA-STD-7009.
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7. National Aeronautics and Space Administration (NASA). *NASA Procedural Requirement, NPR 7150.2D, NASA Software Engineering Requirements*, March 2022. https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7150&s=2B.
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12. Shackelford, J.F., Han, Y.-H., Kim, S., & Kwon, S.-H. (2015). *CRC Materials Science and Engineering Handbook (4th ed.).* CRC Press. https://doi.org/10.1201/b18971

13. NIST Digital Library of Mathematical Functions. National Institute of Standards and Technology (NIST). https://dlmf.nist.gov/.

14. International Organization for Standardization (ISO). ISO 9001:2015, *"Quality Management Systems Requirements,*" September 2015. https://www.iso.org/standard/62085.html#lifecycle.

15. Capability Maturity Model Integration (CMMI) Version 3.0. https://cmmiinstitute.com/

4 DEFINITION OF TERMS.

For this AC, the terms, and definitions from § 401.7 and this list apply.

4.1 Real-World System (RWS).

An actual physical system that has operated, is operating, or will operate which a simulation (e.g., a computer model) emulates.

4.2 Generally Accepted.

Described in standards published by Federal Government or recognized standards organizations, in textbooks that are widely used in educational settings, or in widely cited published documents (journal articles, books, etc.).

5 ACRONYMS.

- 3DOF – Three Degrees of Freedom
- AC – Advisory Circular
- APA –American Psychological Association
- AST – Office of Commercial Space Transportation
- CFR – Code of Federal Regulations
- CMMI –Capability Maturity Model Integration
- CSE – Council of Science Editors
- ECI – Earth Centered Inertial
- FAA – Federal Aviation Administration
- FSA – Flight Safety Analysis
- FHA – Functional Hazard Analysis
- IEEE – Institute of Electrical and Electronics Engineers
- ISBN – International Standard Book Number
- ISO – International Standards Organization
- MIL-STD – Military Standard
- MOC – Means of Compliance
- MPL – Maximum Probable Loss
- NASA – National Aeronautics and Space Administration
- NIST – National Institute of Science and Technology
- OMB – Office of Management and Budget
- RWS – Real World System
- URI – Uniform Resource Identifier
- URL – Uniform Resource Locator
- U.S.C. – United States Code
- U.S. – United States
- V&V – Verification and Validation

6 INTRODUCTION.

Section 450.115 provides requirements that apply to all flight safety analysis regulations, from § 450.117 through § 450.139. This AC primarily discusses paragraph (c) of § 450.115, which contains requirements for how a flight safety method must be described. § 450.115(c) is referenced by § 450.108 and each regulation section from § 450.117 through § 450.135.

6.1 Relationships between paragraphs in § 450.115.

Paragraph (a) of § 450.115 identifies the scenarios that need to be covered in all FSA, so that the analysis comprehensively covers the hazards—and thus the methods need to describe all such scenarios. Paragraph (b) discusses the level of fidelity required – with the fundamental principle that the level of fidelity of a flight safety analysis need only be sufficient to demonstrate compliance with the safety criteria, accounting for uncertainty. Another AC is planned to further discuss level of fidelity and uncertainty. However, importantly, a thorough description of methods required by paragraph (c) is fundamental to demonstrating compliance with paragraph (b). The level of fidelity of an analysis cannot be assessed without an understanding of the method used to perform the analysis. Therefore paragraph (c) requires an applicant to provide information that allows the FAA to assess the method an applicant used to perform the analysis, which thereby allows the FAA to confirm whether an applicant's level of fidelity is sufficient to meet paragraph (b).

7 EXPLANATION OF § 450.115(c).

Section 450.115(c) requires that applications include a description of the flight safety analysis methodology, including identification of:

- The scientific principles and statistical methods used;
- All assumptions and their justifications;
- The rationale for the level of fidelity;
- The evidence for validation and verification required by § 450.101(g);
- The extent to which the benchmark conditions are comparable to the foreseeable. conditions of the intended operations; and
- The extent to which risk mitigations were accounted for in the analyses.

Each of these is discussed in this chapter. However, it is generally helpful to begin a description with an overview of the basic structure of the method, including the conceptual models used and behavior being modeled. Developing a new method is often a major undertaking for applicants and requires commensurate significant review by the FAA. See AC 413.13-1 for other approaches to developing new methods.

7.1 Scientific Principles and Statistical Methods Used.

The first element of § 450.115(c) are the scientific principles and statistical methods used to perform the analysis; this is sometimes referred to as a technical description. The technical description should cover the entire process from gathering input data through to the specific output products that result. The logic and flow of data through the approach should be clear to the reader. The description should not simply reference principles and methods, but needs to show how they are used, i.e. a description of how they are applied to the situation being analyzed. Additionally, it should describe how different elements of the method connect and how the data flows through the process and show iterative and parallel application of principles. Modularizing the description of methods also helps clarity, where the inputs and outputs of each module are explicit. It is common to use flow charts at different levels of detail (e.g., how modules relate and steps within the modules) to illustrate the process. Specific and consistent notation (symbology and indices) should be used to ensure clarity. If a method includes an existing method documented elsewhere, the description should provide a clear mapping to the notation used in the external reference, if it is different.

7.1.1 Scientific Principles.

Scientific principles are based on the scientific method: hypotheses tested and demonstrated using repeatable experiments or other empirical data. The validity of a scientific principle is often limited to a set of conditions. For example, Newton's laws of motion are valid scientific principles, which become inaccurate when an object

approaches the speed of light. There are many scientific principles established in the fields of physics, chemistry, and/or biology, which are generally implemented through the use of equations. A description may sometimes combine principles. Additional assumptions may be applied to allow simplification of existing equations. The technical description should show the derivation of any equations used, starting from established principles. Occasionally, a new principle may be developed from geometric arguments; this should be carefully explained and justified. Considerations for assessing the validity of data and scientific methods are further discussed in paragraphs 8.2.1 and 8.2.2 of this document.

7.1.2 Statistical Methods.

Statistical methods are approaches to describing data and inferring conclusions. Data may be the product of observation/measurement or modeling/simulation. Descriptive statistics provide summaries of gathered data that aid in understanding and reduce the quantity of information to be analyzed. Statistical analysis results in identification of patterns: both the dependence of results on independent variables and the characterization and quantification of uncertainty due to unknown effects. There are variety of approaches to statistical analysis and data science. A structured framework should be followed, such as Exploratory Data Analysis (for an introduction, see Reference 1) or Bayesian analysis (reference 2). Applicants are encouraged to be cautious about developing novel approaches, instead focusing on applying generally accepted (see paragraph 4.2) approaches to the specific topic and referencing such approaches. Considerations of the validity of statistical methods are discussed in paragraph 8.2.3. The applicability of the conclusions and of the predictions to a specific scenario are dependent on the similarity of the scenario to the scenario(s) under which the data was obtained. These are important to characterize as part of the scope of applicability of the method (see paragraph 7.2.1). Statistical analysis should be used to characterize the uncertainties associated with inputs and output from the analysis in order to demonstrate compliance with § 450.115(b).

7.2 **Assumptions and Justifications.**

The description of methods must include the assumptions used and their justifications, per § 450.115(c)(2). An assumption is an axiom[1] or postulate[2] that is relevant to supporting the methods. Justifications provide reasons that support the use of a stated assumption. Assumptions related to methods used to perform analysis should be

[1] A statement accepted as true as the basis for argument or inference. “Axiom.” *Merriam-Webster.com Dictionary*, Merriam-Webster, https://www.merriam-webster.com/dictionary/axiom. Accessed 26 Jul. 2024.

[2] A hypothesis advanced as an essential presupposition, condition, or premise of a train of reasoning. “Postulate.” *Merriam-Webster.com Dictionary*, Merriam-Webster, https://www.merriam-webster.com/dictionary/postulate. Accessed 26 Jul. 2024.

considered in several categories. A first category is the range of applicability, or the scope, for which methods are intended to cover and not cover. A second category includes the assumptions about which physical phenomena are relevant to the modeling. Thus, a technical description should identify the set of conditions or bounds that define when the scientific principles used are established to be valid. A third category covers the assumptions about data availability and uncertainty. A fourth category is about the capabilities of human operators. Careful consideration of assumptions and their justifications is fundamental to ensuring a method is appropriate for the scenarios that will be analyzed and has sufficient fidelity, in accordance with § 450.115(b). It is not possible to prove that every assumption has been identified nor is it appropriate to list the basic assumptions of the scientific method (e.g., consistency of physical laws). At a minimum, the technical description should identify those assumptions that could *potentially be violated* in the application of the method to a particular situation. These include both the environment (e.g. there are no nearby special events) and the vehicle/operation (e.g. effects of slosh on mass properties are negligible due to baffles).

Note: The FAA has found that overlooking important assumptions and insufficient justifications for assumptions are a primary reason that methods are deemed unacceptable.

7.2.1 Scope of the Method.

The description should identify intended uses and permissible use of the method (see Ref 3). This should be listed as a set of constraints or limitations, ideally expressed mathematically, e.g., only when parameter X is less than parameter Y. The scope of a method may be limited for many reasons. One common reason is that the range of data that was used to develop the method is limited, and it is inappropriate to extrapolate beyond the range of the data. Another common reason is that assumptions have been applied to simplify the modeling approach (see paragraph 0).

7.2.2 Physical Phenomena.

The description should identify the assumptions that are made about which physical phenomena are relevant to the models used in the method. These assumptions are often based on the time scale or length scale of the effects being studied. As a very simple example, when dealing with rocket flight, Newtonian physics are normally sufficient; it is unnecessary to consider relativistic or quantum effects. These kinds of assumptions generally make a problem more manageable and easier to model and are necessary to make an analysis practical. Some assumptions may be valid for some methods and not others. For example, for some flight simulation, it is essential to model using six degrees of freedom, but for other (e.g., some malfunctions), it is reasonable to assume fewer degrees of freedom (see the discussion in AC 450.115-1A regarding malfunction trajectory analysis).

7.2.3 Data.

Two key areas of assumptions are important regarding data. First, an analysis often requires data that changes with time. As such, a key assumption is that the data will be available - and available in the timeframe required. A second assumption is that the data accuracy and thoroughness achieve a certain level. The description should identify the assumptions/conditions used regarding the accuracy and timeframe for data input. These two assumptions should normally lead to flight commit criteria to ensure the operation is within the scope of the analysis validity. A second area of assumption is the character of the uncertainty of the data. A statistical model involves terms related to random effects; assumptions are often made about the probability distribution of these errors. A few of the most common assumptions in statistics of data are normality, linearity, uniformity, and in certain cases, the equality of variance. The description should identify all assumptions in the method regarding the nature and extent of the uncertainties for data input.

7.2.4 Human Operators.

The description should identify any assumptions regarding the human operators involved in the method. A process of analysis involves humans as well as software. Most analysis approaches require some level of skill from the analyst; it is an assumption that the analyst has such skills. These skills are an essential element in verifying the proper operation of software, both in terms of using proper inputs and validating outputs. Likewise, humans have practical limits; this is relevant for analysis in terms of the speed they can perform tasks and the ability to perceive distinctions. A specific example is the time it takes a mission flight control officer to identify a failure and initiate flight termination action.

7.3 **Level of Fidelity.**

Section 450.115(c)(3) requires a description of the methodology to include a rationale for the level of fidelity. Assessing fidelity is a comparison of an approach, process, model, or simulation to the real-world. One form of fidelity is accuracy which is the closeness of a parameter or variable (or a set of parameters or variables) within a model, simulation, or experiment to the true value.

Section 450.115(c)(3) is not referencing the justification for the choice of the level of fidelity, but rather the discussion of how the level of fidelity of the method was determined and characterized. Using qualitative terms (e.g., high-fidelity) to describe the fidelity of a method is sometimes misleading and should be avoided.[3] Qualitative terms may be useful for discussion of the *relative* fidelity of different methods.

[3] The FAA recognizes that AC 450.115-1 is titled "High-Fidelity Flight Safety Analysis" in contradiction to the guidance here. This is short-hand language for approaches that were accepted as the highest-fidelity approaches generally used (there exist higher-fidelity approaches).

7.3.1 Bias and Uncertainty.

Instead, a quantitative measure of fidelity should be determined: the bias and uncertainty. Bias is systematic tendency for a prediction to be skewed in "one direction" as compared to the actual value. This may be intentional, such as biasing toward more safety. This may be accomplished by choosing an upper bound instead of a mean value (especially when a "reasonable upper bound" might be easier to justify than the full distribution or as a simplifying approximation). Uncertainty is quantified by a probability distribution of the difference between predictions and the actual value, and both aleatory and epistemic uncertainties should be considered (see Reference 5). A description of uncertainty may utilize a functional form (e.g., Gaussian distribution with mean and standard deviation) or be specified by selected confidence levels. In some cases, assessing bias and uncertainty requires engineering judgment. Characterization of the bias and uncertainty of each method is a key input to demonstrating that the flight safety analysis method has sufficient fidelity to establish compliance with the safety criteria accounting for bias and uncertainty in accordance with § 450.115(b).

7.3.2 Rationale.

Rationale can be considered from two different perspectives. One is the rationale for the choice of the level of fidelity, which of course has implications to the operator. Generally, a higher fidelity model is more costly to implement and operator, but often reduces the mitigations that are required to protect safety thus saving other costs. However, the FAA does not assess these considerations, so they are not relevant and need not be discussed as part of the method. Instead, as noted above, the method needs to present the rationale for the determination and characterization of fidelity. The description should discuss the fidelity of each module (one of a set of separate parts that, when combined, form a complete whole) of the method and then aggregate into a summary description of the fidelity for each method, including characterization of the relative importance of each module to the overall fidelity. The fidelity may be different for different parallel parts of a method (e.g., different fidelity for different failure response modes in § 450.119); these should be characterized separately.

7.4 **Verification and Validation.**

Verification and Validation (V&V) refer to activities performed to determine that a product, service, and/or system meets requirements and specifications and that it fulfills its intended purpose. V&V activities can include testing, analysis, demonstration, and inspection. V&V evidence, as required by § 450.115(c)(4), refers to documentation showing that V&V activities have occurred. V&V evidence can include test procedures and reports, analyses, and demonstration and inspection records. A common misunderstanding involves the scope of V&V, where the scope is too limited. There are many ways an analysis can produce the wrong result: a model can be incorrect for the scenario being analyzed, software can incorrectly implement a model, a user can

incorrectly operate software, etc. Thus, the model, the software and/or hardware, and the processes to operate the model all need to have appropriate V&V.

7.4.1 Verification.

Verification is the evaluation that a product, service, or system complies with a regulation, requirement, specification, and/or imposed condition. In the specific context of § 450.115(c), verification is the evaluation that the implemented process matches the documented approach described in § 450.115(c)(1).

7.4.2 Validation.

Validation is the assurance that a product, service, or system meets the needs of the operation. For a simulation (model), validation demonstrates that it adequately reflects the Real-World System (RWS) (see paragraph 4.1) that it is intended to emulate. Successful validation establishes that the method accomplishes the intended purpose in the intended environment. It often involves acceptance and suitability with operation control needs and natural phenomena. Validation ensures that accuracy, bias, assumptions, and uncertainty satisfy associated requirements. One aspect of validation of simulation tools is benchmarking against information that was not used in the development of the models; a discussion of the relevance of such benchmarks to the actual scenario is required in § 450.115(c)(5).

7.4.3 Standards.

Applicants should follow standard practices for performing V&V. The type of process used depends on the type of element undergoing V&V. Examples of standard practices include:

- For modeling and simulation, NASA-HDBK-7009A (Reference 6 in section 3.4) and MIL-STD-3022 (Reference 3 in section 3.4) each provide a comprehensive approach. However, the scope of these documents do not include V&V of procedures for operational use of resulting software.
- For computing systems, including software, AC 450.141-1 provides an overview and references to specific sources.
- For V&V of processes, procedures, and responsibilities, a quality management system is typically used, such as ISO 9001 (Reference 14 in section 3.4).
- For maintaining on-going V&V of software, the CMMI Model (Reference 15 in section 3.4) provides an approach.

For nearly all methods, all four of these aspects should be addressed in the application material, often even for the same element of a method.

7.4.4 Rigor Based on Level of Criticality.

The appropriate rigor of V&V depends on the level of criticality (see AC 450.141-1 for discussion of levels of criticality). A higher level of criticality should have more rigor in the V&V process. A V&V effort performed by an independent organization provides higher rigor than an internal V&V. As example, for software, the V&V activities for high criticality custom software should include testing by a test team independent of the development division or organization consistent with the intent of 450.141(b)(4). For CMMI, the maturity level indicates the level of rigor. For simple software or tools, the V&V can be quite straightforward, such as two staff independently implementing in a spreadsheet

7.4.5 Evidence.

To demonstrate compliance with the V&V requirement of § 450.115(c)(4), the application should:

- Define levels of criticality and the standards used for V&V for each level of criticality,
- Identify the system, process, and software (items) that are used to perform the analysis,
- Document the rationale for the level of criticality of each item,
- Identify the standards used to perform V&V for each item, and
- Provide sample artifacts of V&V for each item.

7.4.6 Off-the-shelf Items.

Many items that are used in a safety analysis are obtained from market sources and it is difficult, or perhaps impossible, for operators to provide the standards for V&V or artifacts. For generally used items that is not specially designed for launch and reentry analysis, the FAA does not expect operators to provide these. However, the way an operator uses the item is subject to V&V requirements. So, for example, there is no need to provide evidence of V&V for Microsoft Excel, but there is for the implementation in a spreadsheet. For tools that are from market sources that are more specially designed for launch and reentry analysis, the operator is encouraged to discuss with the FAA the extent to which the FAA already has such information. For applicant developed custom software leveraging off-the-shelf code libraries, the applicant is expected to document third party product usage policies that provide for application-specific V&V, see § 450.141(c)(8).

7.5 **Benchmarks.**

Section 450.115(c)(5) requires that the description include "the extent to which the benchmark conditions are comparable to the foreseeable conditions of the intended operations." Benchmarks are data sets of input data and associated results to which an analysis (or part of an analysis) can be compared. Benchmarking is a key element of validation (see above). In some cases, actual events have shown that prior analysis methods were significantly incorrect, typically making incorrect assumptions.

Note: As time progresses, additional benchmarks become available. If new data becomes available that appears to have a material effect on the validity of a method, in accordance with § 450.101(g), the FAA may require consideration of such new information.

7.5.1 Choosing Benchmarks.

Appropriate benchmarks are sometimes difficult to obtain and rarely cover exactly the scenarios that will be modeled by the analysis. Of course, the closer a benchmark is to the actual scenario, the more confidence the benchmarking provides to the analysis—and thus the lower the uncertainty, which is relevant to § 450.115(b). The necessary comprehensiveness of benchmarking corresponds to the level of fidelity of the analysis. A low fidelity method may be benchmarked at the top-level of FSA analysis, demonstrating that the products (hazard areas, risk metrics) are more conservative than a higher-fidelity method. However, for a method where the safety results are critically dependent on a particular sub-model benchmarking should be accomplished at the sub-model level.

7.5.2 Comparison to Benchmarks.

The "extent to which the benchmark conditions are comparable" is an important topic. The discussion should review each benchmark that was considered as part of the validation and compare the conditions to the conditions within the scope of the method identified in paragraph 7.2.1. This discussion also supports the assessment of the level of fidelity of a method (see paragraph 7.3). A method that has limited or no relevant benchmarks inherently has high uncertainty.

7.6 **Risk Mitigations.**

Section 450.115(c)(6) requires discussion of "which risk mitigations are accounted for in the analysis." Mitigations must be described in the functional hazard analysis (FHA), per § 450.107(b). The FSA method should relate applicable FHA mitigations to a specific implementation in the FSA and thus quantified in the analysis. The FSA should account for all flight safety limits and other operational limits identified in the flight commit criteria. For example, a wind-weighted rocket FSA should account for any wind conditions or launcher orientation limits in the normal trajectory variability analysis (§ 450.117). Likewise, risk mitigations might include fault-tolerance that affects the FSA. For example, the FSA for a mission can be completed even if an engine is lost should incorporate this in the normal trajectory analysis (§ 450.117), malfunction trajectory analysis (§ 450.119), and probability of failure (§ 450.131). For each method, the description should identify which of the mitigations in the FHA the method accounts for and any caveats such as significant approximations (covering "the extent to which" from the requirement). An applicant should review the FHA to identify potential impacts of any mitigations on the FSA and discuss the extent to which they are implemented.

8 STANDARD OF SUFFICIENCY.

8.1 Content.

Each flight safety analysis regulation is primarily a set of technical performance requirements: the sections prior to the "Application Requirements" section. The application must show in the description that the method results in compliance with each of these requirements. The application should be explicit about presenting the case for why the method results in compliance. A more thorough and rigorous explanation will reduce iteration during the evaluation process. This could be considered like a "closing argument" in a trial, where the evidence has been presented, and now the logic connecting to the regulation is presented. Although a compliance table may be used, this has often not provided sufficient clarity as to how and why the method demonstrates compliance.

8.1.1 Logic and Mathematics.

The description should include careful exposition of the logic of methodology. This should clearly demonstrate the derivation of the specific method from empirical evidence or generally accepted (see paragraph 4.2) methods. The mathematics used in the analysis needs to be complete, accurate, and well-integrated into the narrative.

8.1.2 Topics.

Usually, many analysis steps are used to provide a comprehensive and valid method for a single regulation. The requirements in a regulation are not necessarily organized by the analysis flow and reflect the interdependence of the nature of the elements of an FSA. For example, § 450.123(b) includes four constraints that apply to the entire method and cannot be satisfied by separate sub-models. The FAA intends to provide checklists for typical elements of the methods within ACs for each regulatory requirement. Generally, the description of each element of each method should include responses to § 450.115(c)(1) and (2), whereas it may be acceptable for the responses to § 450.115(c)(3), (5), and (6) to address a regulation section as a whole. The V&V requirements of § 450.115(c)(4) usually are met on a process by process and software tool by software tool basis. The description of methods should clearly identify these elements.

8.2 Validity.

All analyses used to demonstrate compliance with § 450.101 must be valid in accordance with § 450.101(g). As evidenced by its placement in § 450.101 Safety Criteria, this is a fundamental requirement. Further, in accordance with § 450.37(b), all analyses must demonstrate compliance with § 450.101(g), no equivalent level of safety is allowed. There are four aspects to validity in the regulation, as described in the paragraphs below.

8.2.1 Accurate Data.

Accurate data encompasses both the data upon which scientific models are based and the input data specific to the analysis being performed. Scientific models are based on empirical evidence and experimental results. The data for a specific analysis is based on measurements that are needed as input to the models, including the vehicle properties and the environment. All measurement data has uncertainty; uncertainty must be accounted for when evaluating safety metrics, per § 450.115(b). Accurate data does not mean perfect precision, but instead that which is obtained via valid methods and is applied appropriately for the purpose. For example, inaccurate data would be that obtained using a broken scale or measurements that are inapplicable or outdated. Inappropriate application of data includes extrapolation of measurements outside the domain in which they were measured, especially to different physical regimes or locations.

8.2.2 Accurate Scientific Principles.

Accurate scientific principles are those that are developed through the process of formulating hypotheses and then conducting experiments to test the hypothesis. To evaluate the validity of a method, the following[4] should be considered:

- Whether the technique or theory in question can be, and has been tested;
- Whether it has been passed a peer review;
- Its known or potential error rate;
- The existence and maintenance of standards controlling its operation; and
- Whether it has attracted widespread acceptance within a relevant scientific community. See the definition of "Generally acceptable" in paragraph 4.2.

This standard allows an applicant to use a novel approach, provided it has been developed with the scientific method.

8.2.3 Valid statistical methods.

Valid statistical methods are approaches to analyzing data that are generally accepted (see paragraph 4.2). The starting point is to clearly define the goal of the analysis, and then a statistical analysis can be considered as four steps: collection, analysis, inference, and validation. A complete description of a valid statistical method should include documentation of each of these steps, usually following the structured approach of a standard statistical method (see paragraph 7.1.2). Since the safety criteria are fundamentally statistical measures, statistical approaches are discussed in every FSA AC.

[4] This language is from the U.S. Supreme Court decision, *Daubert v. Merrell Dow Pharm., Inc.*, 509 U.S. 579, 113 S. Ct. 2786, 125 L. Ed. 2d 469 (1993)

8.2.4 Consistency with Past Results.

The final sentence of § 450.101(g) reads:

> The method must produce results consistent with or more conservative than the results available from previous mishaps, tests, or other valid benchmarks, such as higher-fidelity methods.

This connects to the requirements of § 450.115(c)(4) and (5), discussed in paragraphs 7.4 and 7.4 above. As discussed, the availability of benchmarks is limited, but where there are benchmarks, the results of the method must be compared to them. Operations by the applicant are clearly necessary to be considered. The "consistent with or more conservative than" means that any bias in the method should be toward increased public safety. This phase can be most easily understood in the context of the risk analysis products: larger individual risk values, more restrictive flight safety limits, higher predictions of collective risk, etc. For some aspects of flight safety analysis, more conservative is straightforward: the prediction of the consequences of a debris impact should be at least as large as the observed consequences. However, for other areas, especially impact dispersions, conservatism is less direct: dispersion size can be correlated or anti-correlated with the size of the hazard area.

8.3 **Editorial Requirements.**

All application materials must be written and in English per § 413.7. Materials should use correct grammar, syntax, usage, spelling, and punctuation, as well as being consistent in the handling of capitalization, hyphenation, abbreviations, and numbers. As highly technical documents with safety implications, method descriptions should undergo internal substantive review and then thorough copyediting and proofreading before submission. A well-written and edited document is more likely to be technically accurate and is much easier for evaluators to follow. Section 450.45(e)(1) provides additional requirements for the submission of material for a safety approval. This section is listed as requirements for the entire application, but the FAA recognizes that these are more useful as applied to each document. The following paragraphs provide additional understanding of how these requirements apply to descriptions of methods. The FAA does not require any particular style or formatting.

8.3.1 Glossary.

The material should contain a glossary of unique terms and acronyms used in alphabetical order, per 450.45(e)(1)(i). These are typically separate tables or lists in the front matter of a document. Unique terms are those that are not generally known (within the field of the subject of the document) or those that have a precise meaning within the document. The application should use terms as defined in § 401.7; any exceptions should be avoided, and, when unavoidable, specifically noted. Very common acronyms, e.g., U.S. for United States, may be omitted, but all others must be included.

8.3.2 Reference List.

The description should contain a listing of all referenced material, per 450.45(e)(1)(ii). No particular format of references is recommended by the FAA, but a standard format should be used, such as Chicago Manual of Style, Council of Science Editors (CSE) style, American Psychological Association (APA) style, or Institute of Electrical and Electronics Engineers (IEEE) style. The applicant should include the Uniform Resource Identifier (URI), International Standard Book Number (ISBN), or Uniform Resource Locator (URL) for references that are publicly available. For references that are not publicly available, the applicant should be prepared to provide access to them upon FAA request and should proactively provide those that contain significant aspects of the method. Wherever another document is referenced, the reference should indicate specific section, subsection, equation, or page number.

8.3.3 Derivations.

The descriptions must use equations and mathematical relationships derived from or referenced to a recognized standard or text, per 450.45(e)(1)(iii), i.e. one that is generally accepted (see paragraph 4.2). There should be no unsubstantiated claims or technical assumptions. There should be no "orphan" equations; all equations must be cited to an external source or derived within the description. Most equations are limited to certain regimes of applicability and/or include simplifying assumptions. A recognized standard or text should characterize these, and the applicant should be clear as to how these affect the derived results. Handbooks, such as References 12 and 13, provide straightforward sources that allow easy referencing.

8.3.4 Notation.

The descriptions should define all algebraic parameters, per 450.45(e)(1)(iii). These should be defined within the text when first used. They may also be provided as a list of notations used in the front matter.

8.3.5 Units.

The descriptions must include the units of all numerical values provided, per 450.45(e)(1)(iv). Units are often only relevant in the context of a specific coordinate system, especially a reference point, so that should be clear as well. Consistent unit systems should be used to the maximum extent possible.

8.3.6 Diagrams.

All schematic diagrams must include a legend or key that identifies all symbols used, per 450.45(e)(1)(v). All maps and charts should also include a legend or key so that the reader can easily interpret the information. Axes should be labeled clearly, including units where relevant. Applicants should avoid complex figures that require significant discussion to understand. Further, the application should make clear in the text the

conclusions that are drawn from each diagram; it should not be assumed that the reader has the same interpretation of the information.

8.4 **Depth of Detail.**

The FSA methodology should be verifiable, inspectable, and repeatable, which means being explicit about details. The description should be sufficient that it produces consistent results using the same set of input data. Later, with specialized tools, training on the use of those tools, and using the same inputs and following the same approach, one should be able to reproduce consistent results and derive the same conclusion as posted by the applicant's flight safety analysis. The flight safety analysis should be inspectable. Any statements made should be clearly supported by evidence. Two different engineers looking at the provided methodology description should not interpret them differently in a meaningful way. Thus, the descriptions should include equations and/or examples that derive the conceptual approach of the methodology. It is not necessary to provide an algorithmic implementation (e.g., pseudo-code) or software code. Use of standard mathematics such as linear algebra or calculus can be assumed.

8.5 **Review and Revision Process.**

An applicant must submit new and revised flight safety analysis methods to the FAA, and those methods must be accepted, prior to application submission in accordance with § 450.35(a)(1)[5]. The process from initial submission of methods to acceptance has often involved multiple iterations between the applicant and the FAA. Iterations can be reduced by a thorough internal process by the applicant of methods descriptions prior to submission. This vetting process should rigorously scrutinize the documentation: challenging assumptions, identifying logical leaps, and ensuring that language is definitive.

The typical process for review of a description of methods involves the FAA providing feedback to the applicant with the applicant revising and then resubmitting. The FAA normally first performs a checklist review (see paragraph 8.1.2), which is only a screening. The screening does not aim to identify technical issues. At the conclusion of the screen, the FAA typically identifies to applicants of material that is expected but is not found, or that the material has passed the screening. The FAA will not proceed to further evaluation of a description of methods until this screening finds the material sufficient. The further evaluation is typically performed by highly knowledgeable reviewers in the specific analysis area. Feedback from this review typically comes as specific comments to the text along with a summary of the feedback.

[5] See AC 413.13-1 for additional information on how FSA Methods relate to Means of Compliance.

8.5.1 Maturity Rating.

The FAA normally provides a maturity rating as part of its feedback to help applicants understand the significance of the issues in the method. The maturity levels are shown in Table 1. These maturity levels are unrelated to the complete enough assessment, which occurs after application submission, whereas the methods must be accepted prior to submission. Applicants should be aware that it typically requires a significant effort to move up a single maturity level.

Table 1 - Methodology Maturity Levels

Maturity Level	Reason(s)
5 – Very Mature	May need minor clean-up (minor misstatements, reference problems)
4 – Nearly Mature	Documentation is solid, but not yet comprehensive (additional material could expose new issues) Technical approach is nearly acceptable, but there are minor reasons that need to be corrected for the approach to be satisfactory, There are meaningful but not major errors.
3 – In-process	Technical approach appears reasonable, but significant gaps remain for the explanation to be complete or correct. Compliance with § 450.115(c) across the whole analysis has significant gaps.
2 – Immature	Significant concerns about the technical approach (the fundamental idea is sound, but the implementation and/or details need a lot of work). Significantly substandard response to an aspect of § 450.115(c).
1 – Invalid	Fundamental problem(s) with the technical approach, i.e. it does not produce the products needed, or it is not viable for the intended application. Clear lack of understanding of the requirements of an aspect of § 450.115(c)
0 – Not Complete Enough	Does not cover all required technical topics or does not discuss an aspect of § 450.115(c) for each technical topic.

8.5.2 Response to Feedback.

Applicants should carefully review all feedback received and submit a revision of the description of the methods for review. Applications should take care to avoid minimizing the comments. The summary of feedback is particularly important as it aims to provide clear identification of the major issues and their severity. If the applicant feels the FAA feedback indicates that a portion of the material was overlooked, is factually incorrect in the feedback, or is inconsistent with the regulation, the applicant should submit the evidence in writing separate from other responses to feedback. Also, if an applicant would like further explanation of the feedback to assist them in responding, a meeting with the FAA may be requested. Applicants should not use the meeting as forum to debate or to seek assurances on a proposed solution.

8.5.3 Recommendations.

To make this process maximally efficient and reduce iterations, the FAA notes the following:

- Applicants should aim to ensure that all feedback has a comprehensive response within the revised description. Only material in the description of methods document(s) are used as the basis for evaluation (e.g. not other responses to comments).
- Attempts to quickly fix a significant issue in a method are rarely found satisfactory.
- Rigorous internal review of all submissions is recommended. An inadequate response to FAA feedback will prolong the review cycle.
- Applicants should specify, for each comment, where in the revised submission the response has been made.
- Applicants are encouraged to submit both a “red-line” and a “clean” version of description revisions to aid reviewers in finding changes, unless the material has undergone such a significant revision that showing individual changes would not be meaningful.
- Configuration management of documents is very important; documents should be assigned unique identification codes with unique revision numbers. A revision history should be maintained within each document. The accuracy of such information should be verified immediately prior to submittal.

8.6 **Example.**

To illustrate the depth and rigor that provides sufficient material to demonstrate the approach is valid, this section presents two fictional examples. These examples are both descriptions of a three degree of freedom (3DOF) propagation.

8.6.1 Insufficient Description.

An example of a description with insufficient detail is shown in Figure 1. The method is described using a single sentence without any references to the governing mathematics, numerical analysis, or sources of data. This example is an unacceptable submission because there is a wide variety of potential implementations of this that could result in very different results. The FAA cannot determine the fidelity of the physics that are incorporated, whether the numerical approach is valid, or whether the input data is from a suitable source that is processed correctly. Further, without a specification of the software used, there is no basis on which to inspect that the approved software is being used for a particular mission.

Figure 1 - Method Description with Insufficient Detail

Debris impact locations are calculated using a 3DOF propagator that incorporates air density and wind using our in-house tool.

8.6.2 Sufficient Description.

An example of a description with sufficient detail is shown in Figure 2. This description is still less than 200 words, but now is precise. This approach required no model development or mathematical derivation by the applicant, existing approaches are simply linked together. The reference to existing approaches also allows the FAA to quickly evaluate the validity of the approach. These requirements are now sufficient for writing an algorithm to perform this calculation, which is then the basis for verification of the implementation. This further provides an unambiguous basis for an inspection by the FAA.

Figure 2 – Method Description with Sufficient Detail

A standard approach to three degree-of-freedom (3DOF) computational simulation is used to compute trajectories for uncontrolled, unpowered objects. It is implemented in our SB_BallisticPropagation software module. Input data are the initial position and velocity in earth-centered inertial (ECI) coordinates; the object's ballistic coefficient as a function of Mach number; and the specification of a 3-D atmospheric model (e.g., a Global Forecast System forecast). Equations of motion are appropriate for a rotating Earth are used to determine the flight path of an object using a 3DOF simulation approach [1]. The equations are integrated with respect to time using a Runge-Kutta method with the Adams-Bashforth predictor-corrector Ref [2] with an initial timestep of 1E-6 seconds (this timestep is much smaller than any meaningful changes in parameters on the scale of rocket flight). Earth parameters through J2 are from WGS84 [3]. Extraction and transformation of air density, speed of sound, and wind data are discussed in 3rd party software documentation [4]. The specific atmospheric data depends on the analysis phase, as discussed in section X.X. The output is the trajectory (time, position, velocity) of the object in ECI coordinates from the initial state to impact with the Earth's surface at the interval of the integration steps.

1. Weiland, C. (2010). Three and Six Degree of Freedom Trajectory Simulations. In: Computational Space Flight Mechanics. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-13583-5_8
2. William H. Press ... [and others]. (1992). Numerical recipes in C: the art of scientific computing. Cambridge [Cambridgeshire]; New York: Cambridge University Press, ch. 16. https://numerical.recipes/
3. Department of Defense World Geodetic System 1984: Its Definition and Relationships with Local Geodetic Systems, Version 1.0.0, 8 July 2014. https://nsgreg.nga.mil/doc/view?i=4085.
4. XYZ Company, Atmospheric Data Application Programmer's Interface Reference, version 6.1.

OMB Control Number: 2120-0746
Expiration Date: 11/30/2024

Advisory Circular Feedback Form

If you find an error in this AC, have recommendations for improving it, or have suggestions for new items/subjects to be added, you may let us know by (1) emailing this form to 9-AST-ASZ210-Directives@faa.gov, or (2) faxing it to (202) 267-5450.

Subject: Click here to enter text. Date: Click here to enter text.

Please check all appropriate line items:

☐ An error (procedural or typographical) has been noted in paragraph Click here to enter text. on page Click here to enter text..

☐ Recommend paragraph Click here to enter text. on page Click here to enter text. be changed as follows:

Click here to enter text.

☐ In a future change to this AC, please cover the following subject:
(Briefly describe what you want added.)

Click here to enter text.

☐ Other comments:

Click here to enter text.

☐ I would like to discuss the above. Please contact me.

Submitted by: _____ Date: _____