



Sustainable Fuels Safety Boundaries Demarcation Method

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Abstract

Climate change is an increasingly serious problem and reducing carbon dioxide emissions is urgent, but the proportion of carbon emissions from the aviation industry continues to rise. Considering the cost, safety and feasibility of new energy sources, the adoption of Sustainable Aviation Fuels (SAFs) is one of the best options for the aviation industry to achieve the emission reduction target in the short term. Ensuring the safety of SAFs is the bottom-line issue for their large-scale utilization. The American Society for Testing and Materials (ASTM) standard system, which is the primary basis for SAF assessment, has been developed based on experience of conventional aviation fuels (CAFs). The ASTM standards clearly delineate the range for each physicochemical property of SAFs, but there is also a risk of failure within this constraint. In recent years, an Engine-level Safety Assessment Method has been proposed which has the potential to further unlock the potential of SAFs while keeping safety. This paper draws on the core idea of the Engine-level Safety Assessment Method, and the Monte Carlo method is utilized to inverse-map the safety boundaries of the engine to the range of physicochemical properties of the fuel, with the purpose of complementing or integrating the two assessment routes.

Keywords: Sustainable Aviation Fuels; Safety Boundaries; Monte Carlo Methods; Inverse Mapping; Failure Probability.

1. Introduction

With global warming becoming a global focal point, reducing carbon dioxide emissions has become a consensus among all sectors of society. In today's global carbon emission pattern, aviation accounts for 12% of CO₂ emissions from the transportation sector [1]. In addition, passenger demand in the aviation industry continues to grow, with revenue passenger kilometers increasing by nearly 5% per year [2,3]. It can be inferred that by 2050, the direct global CO₂ emissions from aviation will reach 2.5 billion tons [4]. In view of such a serious challenge, the global aviation industry has to accelerate the development of new energy sources to reduce CO₂ emissions.

Sustainable Aviation Fuels (SAFs), characterized by their drop-in, higher energy density and high adaptability to the existing aviation system, offer viable options for realizing the energy transition of the aviation industry as soon as possible. And it has become the focus of research in the aviation system from the manufacturing industry to the transportation industry. Petroleum companies such as Shell [5] have begun process research or realized small-scale production for sustainable aviation fuels. Original Equipment Manufacturers such as Airbus [6] and Boeing [7] have incorporated SAFs into their aircraft research and development (R&D) requirements, and airlines such as Lufthansa [8] have formulated future plans to increase the use of SAFs. In addition, the European Union has enacted legislation to promote the use of sustainable aviation fuels [9]. The development of SAFs has become one of the main routes for the aviation industry to address global warming and the energy crisis [10,11].

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Promoting energy change in aviation has never been more urgent, but airworthiness regulations are still focused mainly on traditional aviation energy sources. Regulators have tacitly assumed that aircraft will only use a few highly restricted and standardized types of aviation kerosene. The standards that limit the use of jet fuel come primarily from standards societies like the American Society for Testing and Materials (ASTM), which constrain jet fuel in terms of its physicochemical properties. This method has naturally been carried over to SAFs with a revised range of physicochemical properties. However, Because of the limitations of feedstocks and processes, there is no complete consistency between SAFs and conventional aviation fuels (CAFs) in terms of hundreds of physicochemical properties. Moreover, the revised range of physicochemical properties lacks an assessment of engine system safety. In order to guarantee the system safety of engines when using SAFs while releasing the constraints of the physicochemical properties for SAFs, the Engine-level Safety Assessment Method has been proposed. This method relies on the experience of using aviation kerosene to evaluate SAFs from the perspective of engine system safety. The method is expected to both improve the system safety level of SAF assessment and release the development potential of SAFs. However, this assessment method has limitations in providing reference for developers and users. Whether it is to provide additional supporting data to the ASTM system, to improve the reference value of the Engine-level Safety Assessment Method, or to integrate the two assessment routes, it can be accomplished by obtaining the range of fuel physicochemical properties by mapping the engine safety boundaries inversely.

This paper compares the ASTM standard system and the Engine-level Safety Assessment Method, combines the advantages of the two assessment routes, and investigates the use of Monte Carlo-based inverse mapping method to determine a more appropriate decoupling constraint range for the physicochemical properties of SAFs. And the application scenarios and development direction of this method are also analyzed.

2. Two Assessment Routes for Sustainable Aviation Fuels

2.1 Existing Standards

Existing fuel standards are mainly industry standards, military standards or association standards cited by regulatory authorities [12]. Taking the most representative Federal Aviation Administration as an example, it has introduced a variety of technical standards, including the Military Details and the ASTM standards, in its Advisory Circular, AC 20-24D [13], as the limitation for the approval of SAFs. Once the evaluated SAF reaches the fuel technical standards, it will be submitted to the airworthiness authorities and OEMs for further approval, and if the SAF is recognized as a drop-in fuel that does not require a change in engine use restrictions, it can be used directly in aviation engines.



Figure 1 – Fuel standards in the ASTM.

Sustainable Aviation Fuels safety boundaries demarcation method

The ASTM standard system is the most important fuel standard among them. In the ASTM standard system, Standard Specification for Aviation Turbine Fuels (ASTM-D1655) [14], Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons (ASTM-D7566) [15] and Standard Practice for Evaluation of New Aviation Turbine Fuels and Fuel Additives (ASTM-D4054) [16] are closely related to aviation fuels, as shown in Figure 1. ASTM-D1655 is the standard for CAFs and is mainly used to constrain the various physicochemical properties of CAFs. With the development of SAFs, ASTM has introduced standards for SAFs. ASTM-D7566 is a standard specification for SAFs that establishes manufacturing requirements for SAFs containing synthetic hydrocarbons. This standard also defines the requirements for blending SAFs with CAFs and the range of physicochemical properties for the blended fuels. In addition, ASTM-D7566 schedules SAFs and their processes that have been evaluated by ASTM-D4054 as purely SAFs for blending with CAFs. ASTM-4054 is a standardized evaluation process to determine acceptable SAFs and their process through testing, original equipment manufacturer review, and expert voting.

TABLE 1 Detailed Requirements of Aviation Turbine Fuels Containing Synthesized Hydrocarbons ^a			
Property		Jet A or Jet A-1	Test Method ^b
COMPOSITION			
Acidity, total mg KOH/g	Max	0.10	D3242/IP 354
Aromatics:			
One of the following requirements shall be met:			
1. Aromatics, volume percent		8 ^c to 25	D1319 or IP 156, ^e D8267, or D8305 ^f
or			
2. Aromatics, volume percent		8.4 ^c to 26.5	D6379/IP 436
Sulfur, mercaptan, ^g mass percent	Max	0.003	D3227/IP 342
Sulfur, total mass percent	Max	0.30	D1266, D2622, D4294, D5453, or IP 336
VOLATILITY			
Distillation			
Distillation temperature, °C:			D86, ^h D2887/IP 406, ⁱ D7344, ^j D7345, ^j IP 123 ^h
10 % recovered, temperature (T10)	Max	205	
50 % recovered, temperature (T50)		Report	
90 % recovered, temperature (T90)		Report	
Final boiling point, temperature	Max	300	
T50 minus T10	Min ^d , L	15	
T90 minus T10	Min ^d , L	40	
Distillation residue, percent	Max	1.5	
Distillation loss, percent	Max	1.5	
Flash point, °C	Min	38 ^m	D56, D3828, ⁿ D7236, ⁿ IP 170, ⁿ IP 523, ⁿ IP 534 ⁿ
Density at 15 °C, kg/m ³		775 to 840	D1298, IP 160, D4052, IP 365
FLUIDITY			
Freezing point, °C	Max	-40 Jet A ^o -47 Jet A-1 ^o	D5972/IP 435, D7153/IP 529, D7154 or IP 528, or D2386/IP 16
VISCOSITY			
One of the following requirements shall be met (whichever is applicable):			
1. The following requirement shall be met for semi-synthetic jet fuel containing Annex A1 or Annex A4 synthesized components blended in accordance with 6.1.1 or 6.1.4, respectively:			
Viscosity -20 °C, mm ² /s ^p	Max	8.0	D445 or IP 71, Section 1, D7042, ^o D7945
or			
2. The following requirement shall be met for semi-synthetic jet fuel containing Annex A5 synthetic blend components blended at less than or equal to 30 % by volume in accordance with 6.1.5:			
Viscosity -20 °C, mm ² /s ^p	Max	8.0	D445 or IP 71, Section 1, D7042, ^o D7945
or			
3. The following requirements shall be met for semi-synthetic jet fuel containing Annex A2, or Annex A3, or Annex A6, or Annex A7, or Annex A8 synthetic blend components blended in accordance with 6.1.2, or 6.1.3, or 6.1.6, or 6.1.7, or 6.1.8, respectively:			
Viscosity -20 °C, mm ² /s ^p	Max	8.0	D445 or IP 71, Section 1, D7042, ^o D7945
and			
Viscosity -40 °C, mm ² /s ^p	Max	12	D445 ^q or IP 71, Section 1, ^r D7042, ^o D7945
or			
4. The following requirements shall be met for semi-synthetic jet fuel containing Annex A5 synthetic blend components blended at greater than 30 % by volume in accordance with 6.1.5:			
Viscosity -20 °C, mm ² /s ^p	Max	8.0	D445 or IP 71, Section 1, D7042, ^o D7945
and			
Viscosity -40 °C, mm ² /s ^p	Max	12	D445 ^q or IP 71, Section 1, ^r D7042, ^o D7945
LUBRICITY			
Lubricity ² mm	Max	0.85	D5001
COMBUSTION			
Net heat of combustion, MJ/kg	Min	42.8 ^t	D4529, D3338, D4809 or IP 12
One of the following requirements shall be met:			
(1) Smoke point, mm, or	Min	25.0	D1322/IP 598
(2) Smoke point, mm, and	Min	18.0	D1322/IP 598
Naphthalenes, volume, percent	Max	3.0	D1840 or D8305 ^u
CORROSION			
Copper strip, 2 h at 100 °C	Max	No. 1	D130 or IP 154
THERMAL STABILITY^v			
2.5 h at control temperature of 260 °C, min			D3241 ^w /IP 323 ^w
Filter pressure drop, mm Hg	Max	25	
Tube rating: One of the following requirements shall be met: ^x			
(1) Annex A1 VTR, VTR Color Code	Less than	3	
		No peacock or abnormal color deposits	
TABLE 1 Continued			
Property		Jet A or Jet A-1	Test Method ^b
(2) Annex A2 ITR or Annex A3 ETR, or Annex A4 MWETR, nm avg over area of 2.5 mm ²	Max	85	
CONTAMINANTS			
Existent gum, mg/100 mL	Max	7	D381, IP 540
Microseparometer, ² Rating			D3948
Without electrical conductivity additive	Min	85	
With electrical conductivity additive	Min	70	
ADDITIVES			
Electrical conductivity, pS/m		See 6.3 y	D2624/IP 274

Figure 2 – Detailed requirements of aviation turbine fuels containing synthesized hydrocarbons [15].

It is obvious that the ASTM standard system is based on the experience of the CAFs, and sets requirements for the physicochemical properties of SAFs, As shown in Figure 2. With the development of SAFs, adjusting and clarifying the existing range of physicochemical properties for SAFs has become an important part of the revision for ASTM standards in recent years [17].

2.2 Engine-level Safety Assessment Method

In order to both improve the system safety level of SAF assessment and release the development potential of SAFs. Some scholars have proposed a safety assessment method for SAFs at the engine level from the system safety perspective. The Engine-level Safety Assessment Method focuses directly on the safety of the engine itself and utilizes the data on the application of CAFs in aircraft engines as the basis for assessing the safety of SAFs [18].

Specifically, the Engine-level Safety Assessment Method employs the idea of relative safety evaluation to assess the safety of SAFs. By collecting the operating data of a standard engine using CAFs, a safety boundary of the engine operation is obtained. The safety of SAFs was then evaluated by comparing the similarity of the operational data from standard engines after using CAFs and SAFs. In the similarity check, it is necessary to select data, which called Safety -Critical Parameters (SCP) that can represent the safety level of Safety-Critical systems. The concept of SCP has been expanded based on the Safety-Critical systems [19-23], and the complete SCP can reflect the safety level of the whole engine.

The Engine-level Safety Assessment Method is not restricted to the physicochemical properties of the fuel and starts directly from the engine operation data, the core idea is shown in Figure 3. Determine engine safety boundaries in advance, and the coupled effects of different physicochemical properties of fuels on engine safety can be analyzed directly, which can improve the safety level of the assessment results. The standard engine concept proposed by the Engine-level Safety Assessment Method also improves the applicability of the assessment results [18].

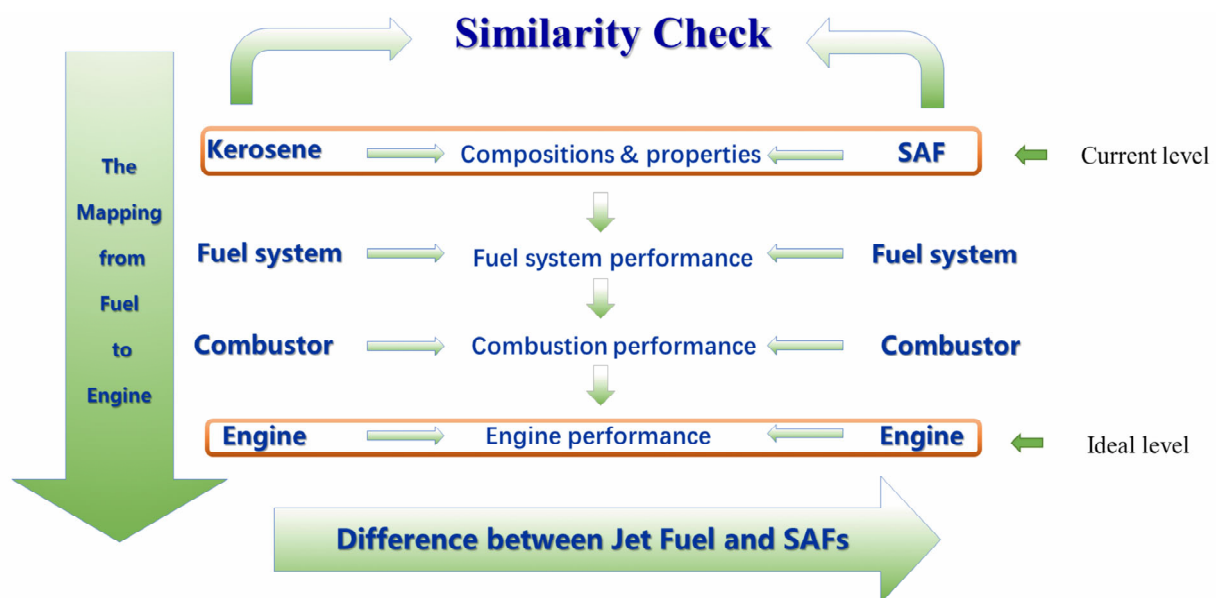


Figure 3 – Core idea of Engine-level Safety Assessment Method [18].

2.3 Summary of comparisons

The ASTM standard system specifies physiochemical property ranges for SAFs based on CAFs, and the requirements are clear to both the developer and user of the fuel. However, ASTM Standards May Lack Some Data Support for Engine System Safety. Besides, the means by which the ASTM

standard constrains different physicochemical properties separately may introduce some decoupling errors.

The Engine-level Safety Assessment Method is directly from the perspective of engine system safety, and the safety boundary of the engine level can analyze the coupling effects of different physicochemical properties of fuels. But it mainly assesses fuels with defined physicochemical properties, and cannot give clear safety requirements of fuel's physicochemical properties before the assessment. Therefore, while this method is capable of analyzing the coupled effects of multiple physicochemical properties in fuels on engine safety and potentially releasing the range of physicochemical property constraints for SAFs, it has some limitations in serving as a reference for developers and users of fuels.

Figure 4 compares the advantages and disadvantages of the two assessment routes. It can be seen that the Engine-level Safety Assessment Method is more generic and more likely to release the level of constraints on the individual physicochemical properties for SAFs, whereas the ASTM standards is more informative for developers and users.

In summary, if the respective ranges of fuel physicochemical properties can be scientifically determined, it is equivalent to scientifically delineating the decoupled safety boundary of SAFs. Not only can it provide support for the physicochemical property requirements of the ASTM standard system, but it can also enhance the reference value of the Engine-level Safety Assessment Method. Finally, success in unlocking the potential of sustainable aviation fuels

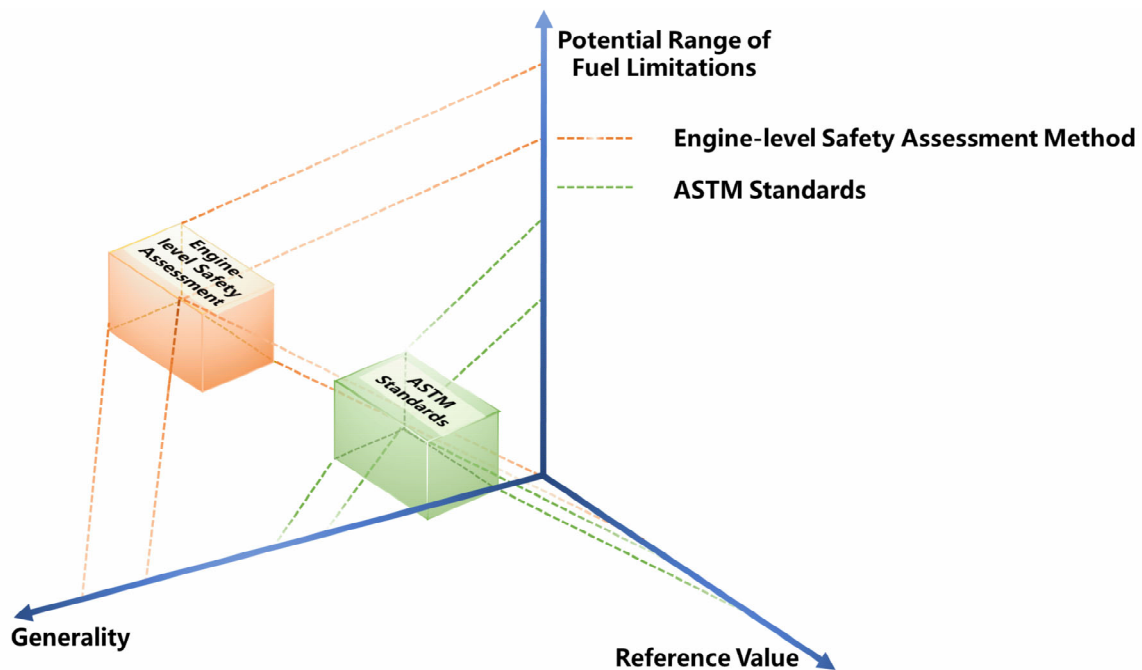


Figure 4 – Advantages of the two assessment routes compared.

3. Monte Carlo-based Method for Determining the Decoupling Safety Boundaries of a Sustainable Aviation Fuel

The Engine-level Safety Assessment Method has the potential to release the range of physicochemical properties for SAFs, but it has some limitations in serving as a reference for developers and users of fuels. And the ASTM standard system has a clearer and more understandable form of constraints on SAFs, but lacks an analysis of engine system safety. If the idea of the Engine-level Safety Assessment Method can be utilized to obtain the fuel safety boundaries through inverse mapping, it can not only add a new support basis for the ASTM standard,

but also improve the reference value of the Engine-level Safety Assessment Method.

Unfortunately, on the one hand, there is a lack of tools to analyze the results of fuel use to realize the inverse mapping of the physicochemical properties for fuels. On the other hand, since the safety boundaries of an engine are the result of the coupled expression from various physicochemical properties of the fuel at the engine level, it is difficult to have a suitable form to express the safety boundaries of the coupled physicochemical properties at the fuel level, and it is not possible to achieve a perfect mapping between the safety boundaries of the two levels.

In order to solve the first problem, this paper adopts the reverse thinking. Determine the fuel physicochemical properties first and then forward map to the engine level for safety assessment. This requires constructing a model that can recognize the effects of different physicochemical properties on the operating state of the engine, and models that can perform fuel sensitivity analyses often meet this requirement. In order to solve the second problem, this paper draws on the expression form of the ASTM standard system, adopts Monte Carlo sampling to solve the problem that cannot measure the failure probability of the fuel safety boundaries introduced by decoupling the different physicochemical properties, and realizes the approximate perfect mapping between the engine safety boundaries and the decoupled fuel safety boundaries.

Assuming that both levels of safety boundaries are related to only three factors, Figure 5 gives the mapping logic of the fuel and engine safety boundaries, while the mapped out 2D spaces explain why decoupling introduces errors.

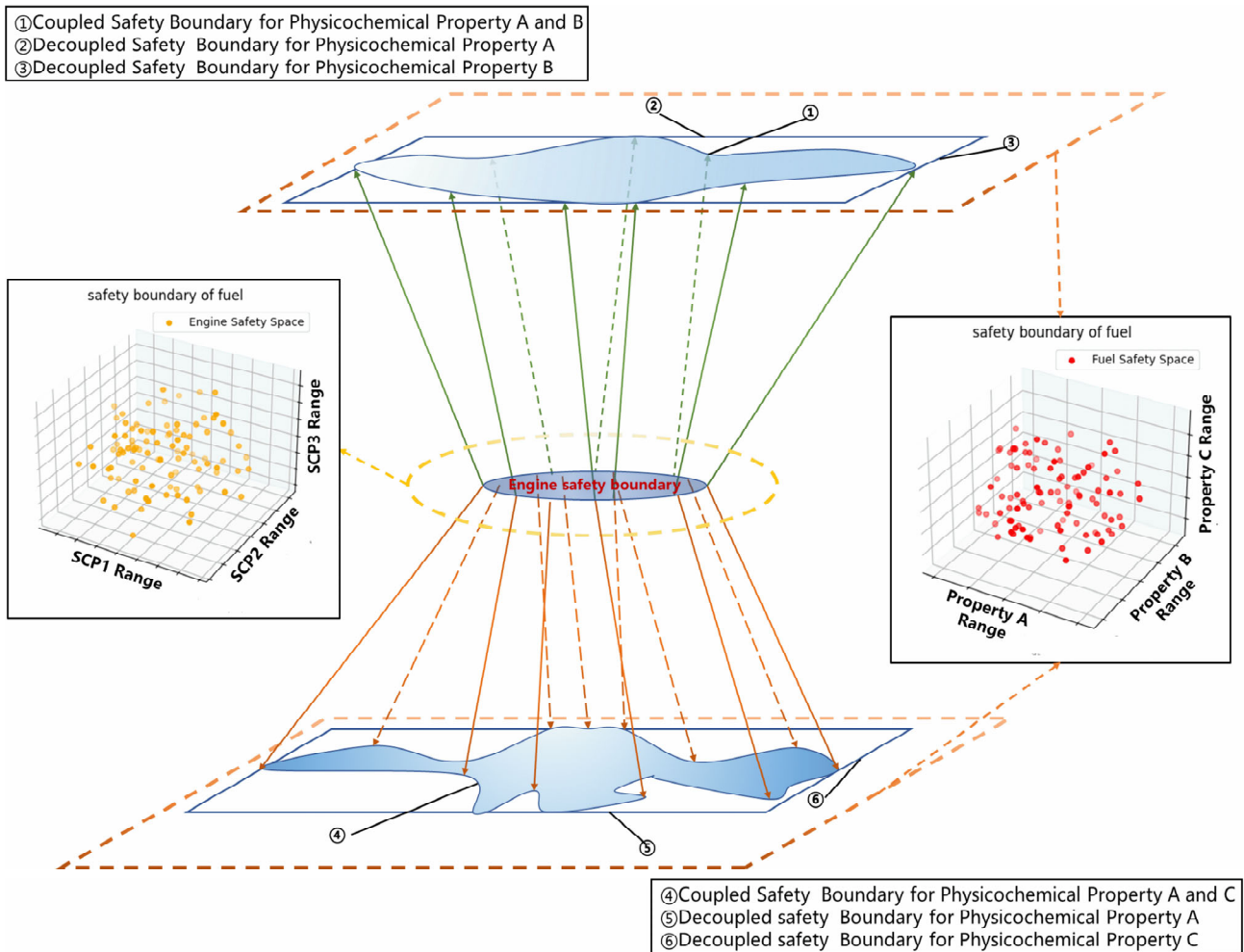


Figure 5 – Safety boundary inverse mapping logic.

3.1 A Forward Mapping Tool Sensitive to Fuel Physicochemical Properties

Due to the lack of a tool to inverse map the physicochemical properties of fuels based on the results of fuel usage, a method of determining the physicochemical properties of fuels and then forward mapping them to the engine level for safety assessment can only be used. Then it is necessary to construct an engine model as a tool for forward mapping. Most of the existing engine models are low-dimensional models constructed by the component method or the fluid network method, which are poor in recognizing SCPs and physicochemical properties [24,25]. If we want to perform forward mapping and safety assessment through model simulation, firstly, the model needs to be able to represent the results produced using fuels with different physicochemical parameters, which requires the model to be sensitive to the physicochemical properties of the fuel, and secondly, the model needs to increase the identification function of all SCPs. If a model can be used to perform a fuel sensitivity analysis, then the model has both of the above requirements. Modeling with mixed dimensionality using high and low dimensions is one of the methods that can be adopted [26], as shown in Figure 6.

There are numerous parameters of physicochemical properties of fuels and the sensitivity analysis is required to identify the magnitude of influence of each parameter on the results. Sensitivity analysis methods play an important role in systematic analysis and can be categorized into two main groups, local sensitivity analysis and global sensitivity analysis, depending on the parameter explored. Local sensitivities vary only the input variables under study at a time, and their results are also related to the state in which the rest of the variables are located, and thus are valid only within a small range of parameters. Global sensitivity analyses in which all input variables change at the same time allow the exploration of a larger range of input variables and a larger scope of applicability of the analysis results.

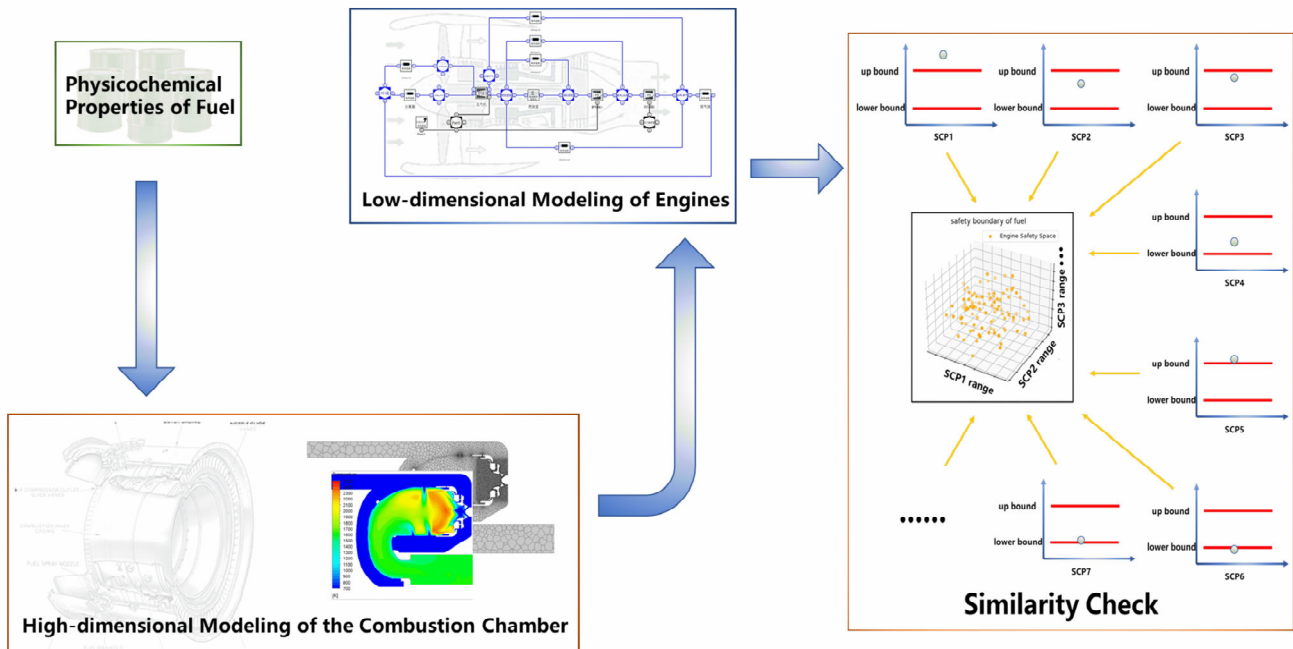


Figure 6 – Conceptual diagram of the forward mapping tool.

The sensitivity analysis in the Engine-level Safety Assessment Method is mainly based on test data, but it can also be analyzed by simulation through the establishment of engine mixed-dimensional model in advance. Zooming technology mainly used in the mixed-dimensional model can be used to analyze the performance of the whole engine based on the characteristics of the components solved by the high-precision model, which is a crucial technology for realizing the high-precision simulation

of the whole aero-engine and its components [27,28].

In this paper, the feasibility of the sensitivity analysis method through simulation is investigated by using the De-coupled technique [26], as shown in figure 7. Firstly, the high-dimensional information of the critical concern component is obtained by simulating it beforehand and establishing the characteristic map of it. Subsequently, a low-dimensional model of the engine is built, and the characteristic map is replaced with the component of interest. Finally, iterative solution is performed to obtain the simulation results. Fortunately, the mixed-dimensional model is able to identify the impact of different physicochemical properties on the safety of the engine. The sensitivity analysis capability of the mixed-dimensional model makes inverse mapping possible.

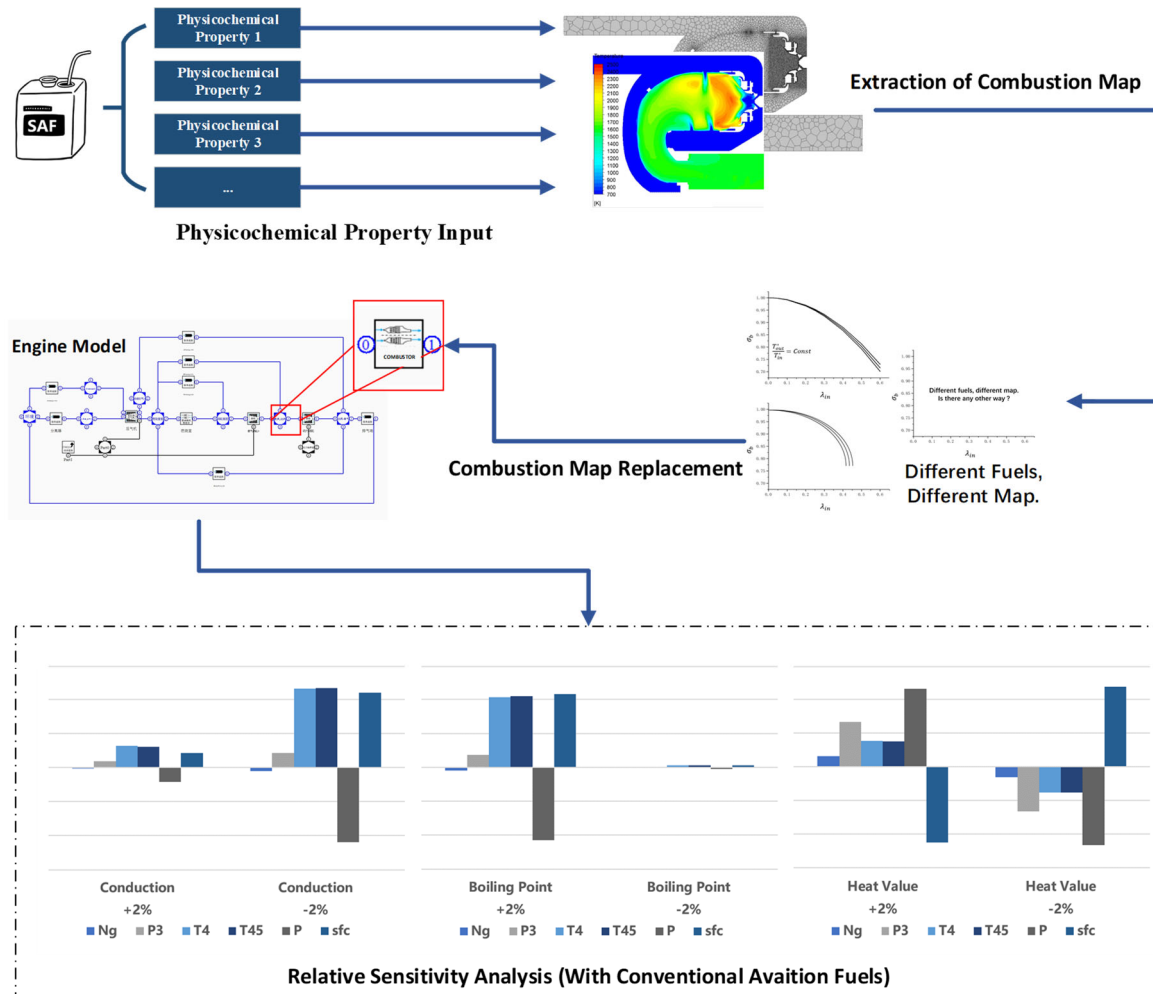


Figure 7 – Forward mapping tool capable of fuel sensitivity analysis.

3.2 Inverse Mapping Method for SAFs Safety Boundaries Based on Monte Carlo Method

Constructing a forward mapping tool that is sensitive to the physicochemical properties of the fuel is only equivalent to replacing the Engine-level Safety Assessment Method from test-based to simulation-based, but the critical to complementing or integrating the two assessment routes is to inversely map the engine safety boundaries to the fuel safety boundaries, and the Monte Carlo method needs to be adopted at the same time. There are two advantages of using Monte Carlo method, on the one hand, the correspondence between a large number of sampling results and the forward mapping results is established, and the fuel safety boundaries can be delineated by judging the relationship between the forward mapping results and the engine safety boundaries. On the other

hand, the better expression form of fuel safety boundaries comes from the ASTM standard system, which is to limit the range of each physicochemical property separately. Obviously, this expression form simply decouples the relationship between different physicochemical properties, and decoupling errors are inevitably introduced in the process. The probabilities obtained by using Monte Carlo method can exactly measure the error introduced by decoupling.

Monte Carlo methods are a typical application of the law of large numbers, which is essentially to estimate the probability of a desired event in terms of a calculated frequency [30]. With the help of Monte Carlo method, the decoupling mapping of the engine safety boundaries at the fuel level can be approximated. Firstly, a fuel level decoupling safety boundary can be determined based on experience, and then the simulation tool can be used to evaluate this decoupling safety boundary and realize the inverse mapping of the engine safety boundary. Evaluating the decoupling safety boundary is mainly based on Monte Carlo idea, taking a large number of samples in the decoupling safety boundary and performing forward mapping, and finally obtaining the failure probability of the decoupling safety boundary by analyzing the relationship between each mapping result and the engine safety boundary.

In details, this method requires four parts: the delineation of decoupled safety boundaries, combination sampling of fuel physicochemical properties, simulation of sampled fuels, and analysis and evaluation of the data, , as shown in figure 8.

First, the decoupling safety boundaries for Monte Carlo sampling needs to be determined, i.e., the constraint ranges for each physicochemical property of the fuel need to be determined. The decoupling safety boundaries can be defined based on a priori knowledge or on the user's own needs. Therefore, the constraints can be defined by ASTM as the standard develops or by the developers and users of the fuel based on their own needs.

Next, sampling is performed within the defined decoupled safety boundary. Since the effect of fuel physicochemical property types on engine safety is unknown, the importance of each physicochemical property should be equivalent. A random number is generated within the pre-determined range of physicochemical properties and this value is used as the parameter for that physicochemical property. When all the physicochemical property categories have been traversed, a potential SAF is obtained and a sampling is completed. Since the nature of Monte Carlo is the law of large numbers, the number of samples taken is critical to the probability of the outcome. The number of samples should be determined based on the probabilistic accuracy, which is generally two orders of magnitude higher than the reciprocal of the probabilistic accuracy. The empirical requirements for random sampling in the aero-engine industry are generally in the millions. In existing aero-engine probabilistic risk studies, after the sample size reaches 10^6 , the relative error and coefficient of variation of the conclusions converge to a relatively small acceptable range [31].

After that, the sampling results need to be simulated to obtain data on the SCPs of the engine. A simulation model can be established based on the standard engine in the Engine-level Safety Assessment Method to improve the representativeness of the simulation results. Considering the working requirements of the simulation model, it should have the following characteristics: first, the simulation model should have the ability to recognize the SCPs of the whole engine, so that it can evaluate the safety level of the engine. Second, the simulation model should have a greater ability to distinguish physicochemical properties. It can reflect the influence of different SAFs on the SCPs of the whole aircraft. Thirdly, the simulation model should have faster computational capability to avoid occupying a large amount of computational resource. In this paper, a De-coupled method is used, but in fact there are many other ways to construct a mixed-dimensional model.

Finally, the simulation result data would be analyzed and evaluated. A database of the corresponding SCPs of CAFs should be available prior to the relative safety evaluation. The database is obtained by analyzing all CAF types with the same simulation model. During the evaluation, the SCPs obtained from the simulation are compared with the database, and the direction and degree of change are analyzed to evaluate the impact of the SAFs on the safety of the engine. When only a small fraction

of the SCPs exceeds the database range, the safety of the SAFs can be evaluated by analyzing the safety of the safety-critical system at this time [32].

By completing the above four steps, one forward mapping of a SAF is finished. Repeat the sampling enough times to count the frequency of all samples that don't pass the safety assessment and take this frequency as the failure probability of the delineated decoupled safety boundary.

Ultimately, a decoupled safety boundary for the fuel level can be formed and the corresponding failure probability can be obtained. This probability not only measures the error introduced due to the decoupling of physicochemical properties, but also can be used to characterize the probability that the fuel in this decoupled safety boundary will pass the safety assessment.

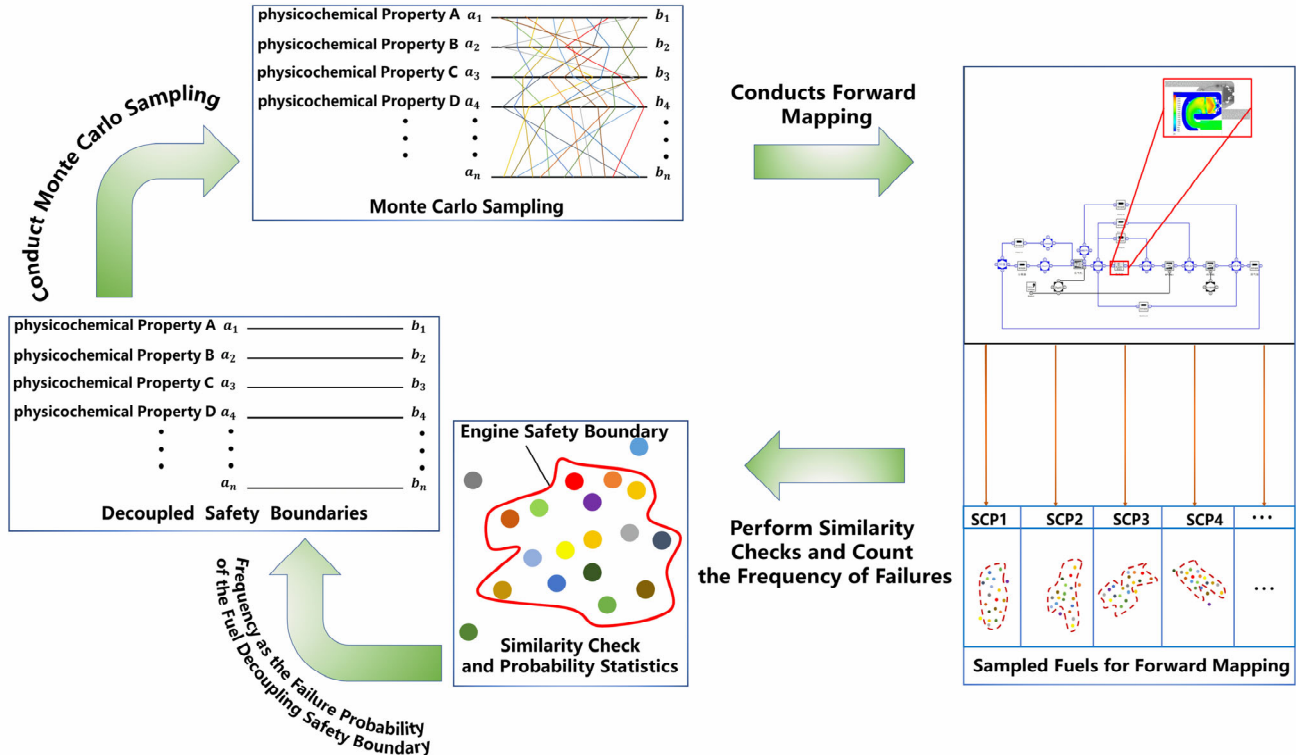


Figure 8 – Inverse mapping based on Monte Carlo methods.

4. Applications and outlook

There are wide application scenarios for the SAF safety boundaries demarcation method, as shown in figure 9.

As for the ASTM standard system, this method can be used to adjust the limiting range of each physicochemical property, while the obtained probability can measure the error introduced by decoupling. As for the Engine-level Safety Assessment Method, this method can provide the fuel safety boundaries in advance as a prerequisite. On the one hand, it can terminate unnecessary assessments. Specifically, both assessment routes could use this method to identify multiple tables of fuel physicochemical property limits, paired with corresponding failure probabilities, as the first step in the assessment. On the other hand, it can be a guideline for fuel developers. Developers can adopt this method to analyze the passing probability of potential research results in advance based on process and experience. The users can also adopt this method to study the risk of blending and using different SAFs. For fuel developers and users, the range of physicochemical properties of developed or blended fuels will be approximated according to the level of their process or the type of fuel used. By using this method, the probability that a future product will pass the assessment could be estimated, helping developers and users to adjust the direction of their research.

When SAFs or blended fuels are determined, the forward mapping tool in this method also allows for assessment through simulation, which can lead to early detection of problems and reduce R&D costs. Besides, the forward mapping tool is not set in stone. As SAFs are evaluated in standard engines, the simulation model, modified by the test data, can have a higher evaluation accuracy. In addition, if the evaluation capability of this method is to be improved, component-level simulation can be added to evaluate the impact of SAFs on engine safety in multiple dimensions.

Moreover, universities in China are also trying various methods including the method of this paper in order to extend the range of physicochemical properties for SAFs while keeping the safety.

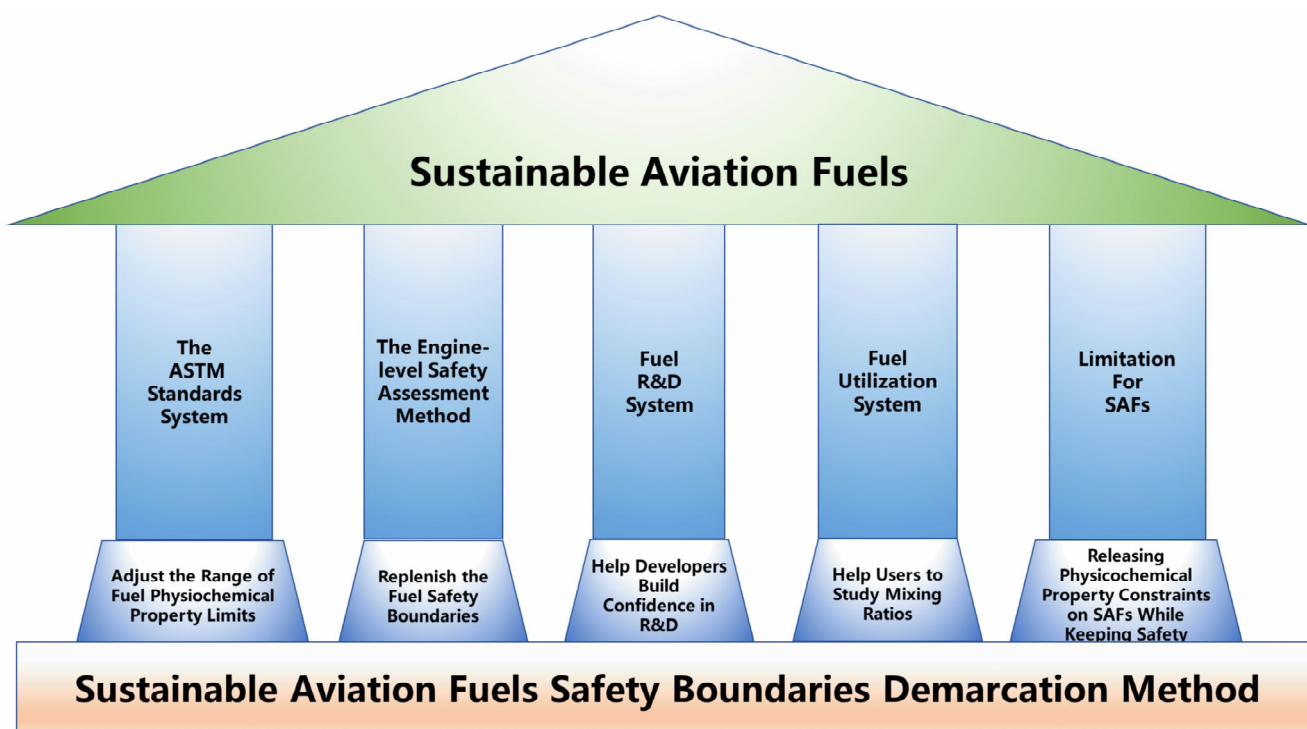


Figure 9 – Directions for the application of SAFs safety boundaries demarcation method.

5. Conclusion

Based on two existing assessment routes for SAFs, this paper proposes a method to inverse map the safety boundaries of fuel physicochemical properties from the engine safety boundaries. Since direct inverse mapping is not possible, this paper obtains the relationship between fuel physicochemical properties and fuel safety boundaries through forward mapping. Then the need for forward mapping tools is presented. Meanwhile, considering that the approximate inverse mapping method will introduce decoupling error to the fuel safety boundaries, this paper adopts the Monte Carlo method to obtain the failure probability of the fuel safety boundaries. This probability precisely solves the problem that the ASTM standard limits the range of each physicochemical property separately but does not measure the decoupling error.

The SAF safety boundaries demarcation method can not only provide support for the physicochemical property requirements of the ASTM standard system, but also enrich the evaluation process of Engine-level Safety Assessment Method. It is beneficial to assist fuel developers to formulate the direction of R&D and help fuel users to determine the way of use. It will also reduce the uncertainty in the R&D process of SAFs and reduce unnecessary sunk costs. As a result, the R&D of SAFs will be intensified, market confidence will be strengthened, and the current situation of low utilization rate and blending ratio of SAFs will be solved.

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