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Reliability-based Approaches for Safety Margin Assessment in the French Nuclear Industry

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ABSTRACT

The prevention of the fast fracture damage of the mechanical equipment important for the safety of nuclear islands of the French PWR relies on deterministic rules. These rules include flaw acceptance criteria involving safety factors applied to characteristic values (implicit margins) of the physical variables. The sets of safety factors that are currently under application in the industrial analyses with the agreement of the Safety Authority, are distributed across the two main physical parameters and have partly been based on a semi-probabilistic approach.

After presenting the generic probabilistic pro-codification approach this paper shows its application to the evaluation of the performances of the existing regulatory flaw acceptance criteria. This application can be carried out in a realistic manner or in a more simplified one. These two approaches are applied to representative mechanical components. Their results are consistent.

KEY WORDS

Safety margin, probabilistic methods, structural reliability, fast fracture, flaw acceptance criteria, codification, RSE-M, fracture mechanics, nuclear, power plant, pressure equipment

INTRODUCTION

Safety Margins : Overview

Ever since man has been building durable structures, they have been assessed by finding the ratio between:

The maximum stress that the material can withstand (i.e. the material strength),

The applied maximum stress that it is assumed to experience during the structure's design life.

This ratio, known as the safety factor or margin, must be sufficient for the structure to be deemed safe.

Safety margins are used to guarantee several safety issues (staff, surrounding population, environmental protection). They appear in all branches of industry.

Note also that the term « margin » has many meanings detailed in [1]. The most frequent are as follows :

- overall safety factor ;
- partial safety factor
- characteristic value (or reference value) of a variable.

Reliability-Based Approaches

It is important to begin by restating the *distinction between reliability-based approaches* and *probabilistic approaches***,** as these expressions are sometimes viewed as synonymous (like in this paper). It is worth noting that the reliability can be evaluated in a deterministic way : a deterministic criterion enables to assess if the structure is reliable or not. Conversely, probabilistic approaches can be used for purposes other than reliability analysis, and can be applied to phenomena other than physical phenomena.

Probabilistic (and reliability-based) approaches have been increasingly used at EDF in the last decade. The probabilistic approach to calibrate safety factors was launched in 1994. It was a support to industrial codification of the safety coefficients. It is now used to evaluate the performances of the safety factor sets that are currently under application.

SAFETY FACTOR CODIFICATION IN THE FRENCH NUCLEAR INDUSTRY

Physical problem

The presence in nuclear plant unit structures of margins relating to foreseeable damage is supposed to ensure the safe operation of facilities. In this paper, we intend to look more specifically at the risk of fast fracture, which is a type of damage to be prevented wherever possible in equipment considered important for safety. According to Fracture Mechanics, the fast fracture phenomenon encompasses two failure modes in structures containing a flaw: the initiation of tearing at the tip of a crack and the unstable extension of this ductile tear; these two failure modes are similar in materials subject to loads in their brittle domain.

Former practices

In the past, the ability of a nuclear component to withstand loadings with a flaw (such as a crack) was evaluated using an essentially deterministic approach, although involving certain underlying probabilistic notions. In "generic" flaw acceptance analyses, the degree of conservatism of the analyses performed was expressed in terms of an overall safety factor (see Table I). The overall safety factor is defined as the ratio between a parameter characterizing a material's strength ($J_{0.2}$ or K_{Ic}) and a parameter characterizing the applied stress ("applied" K or J). An analysis is only deemed to be conservative if this safety factor is 1 or higher.

Changing practices during the 1990's

In response to the inadequacies of the overall safety factor-based approach, a new approach was developed, which consisted in applying specific safety factors to the parameters used in acceptance analyses. The problem then was one of assigning suitable values to these factors, and distributing them appropriately between parameters. This new strategy was introduced in the 1997 edition of the RSE-M code [1].

A probabilistic methodology for determining safety margins was developed in support of the RSE-M codification, based on the link between reliability targets and the sets of safety factors associated with the various parameters' implicit margins. This methodology made it possible to reveal the sometimes very large degree of conservatism of the safety factors detailed in the French Safety Authority's "Operation" Decree. However, while accepting these safety factors as indispensable, we need to use a probabilistic approach to assess the failure probability – or more accurately, the residual risk – that results. Demonstrating that failure probabilities in practical applications are extremely low would then tend to suggest that these factors are excessively restrictive.

The French Safety Authority "Operation" Decree and Memorandum of application

These regulatory documents issued by the French Safety Authority came into effect on 5th February 2000. They cover the main primary system (MPS)[1] and main secondary system (MSS). Their scope is narrower than that of the RSE-M described below, as they only concern class 1 and some class 2 components. They remain, however, the regulatory reference for MPS/MSS flaw acceptance analyses.

The "Operation" Decree

Flaw evaluation is covered in sub-paragraph (article) 13 of Chapter III of the Decree [2]. It is based on a deterministic approach with an overall safety factor applied to loading only. The table of minimum safety factor values is as follows:

Table 1 - Regulatory coefficients displayed by the « Operation » Decree

	ductile instability (or cleavage initiation)	ductile initiation
Category 2 (Level A) normal and upset loading conditions	2	1.3
Category 3 (Level C) emergency conditions	1.6	1.1
Category 4 (Level D) faulted conditions	1.2	-

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[1] The MPS comprises all pressurised containment systems that cannot be isolated from the reactor.

The "Operation" Memorandum of application

The Memorandum sets out the practical arrangements for applying the Decree. Sub-paragraph 13 of the Memorandum states, with respect to the Decree, that in certain cases, partial factors distributed across several parameters may be applied, « provided data relating to the statistical dispersion of the various parameters used in the analysis is available ».

The RSE-M code

The RSE-M code (Règles de Surveillance en Exploitation des matériels Mécaniques des îlots nucléaires REP - *In-service inspection rules for the Mechanical Components of PWR nuclear islands*) is similar to ASME code section XI. It "defines the minimum compulsory standard guidelines applicable to all maintenance tasks performed on pressurized mechanical equipment and mountings in safety classes 1, 2 and 3 as defined in the plant safety assessment report". It therefore notably sets out the acceptance criteria for any flaws detected during operation that do not fall into the categories defined in the flaw acceptability tables. These criteria are based on three considerations:

- Simplified mechanical analysis methods;
- Safety factors applicable to the physical quantities used in the relevant models;
- In the case of mechanical properties of materials, accurate typical numerical values for use in the mechanical calculations.

EDF baseline for RSE-M application

In order to make the RSE-M code compliant with the Decree and Memorandum of 10th November 1999, EDF consulted with the Safety Authority and produced a baseline for applying RSE-M corresponding to current industry practice, as reflected by the acceptance analyses conducted by EDF.

The RSE-M application baseline, which capitalizes on the possibilities offered by the Memorandum, contains sets of factors that sometimes differ from those in the Decree. This means that when checking that flaws are not subject to ductile instability, the overall safety factor specified by the Decree is broken down into one partial safety factor for the load and a second partial safety factor for the material parameter involved in the failure criterion (e.g. the initiation energy J_{02}). This progress was partly obtained by applying the probabilistic approach during the preparation of the new "Operation" Decree.

THE GENERAL PRO-CODIFICATION APPROACH

This approach has been presented in [3]. It refers to a description that has been commonly adopted in other industrial fields [4].

A Five-Step Procedure

The basic pro-codification approach is based on five clearly identified steps:

Step 1: Determine the code scope (i.e. the structures whose safety must be ensured)

Step 2: Determine the code targets (i.e. the required safety level)

Step 3: Determine the regularity of the various operating situations encountered

Step 4: Decide on the code format (i.e. the type of mathematical formulation used to ensure safety)

Step 5: Select a means of evaluating code performance, i.e. measuring the discrepancy between the code's targets and what it actually ensures.

These steps are illustrated in figure 1 below. The decision to use reliability-based methods affects each of these steps. Note that step 3 is intrinsically probabilistic, and is always involved, even when defining codes with deterministic formats (i.e. ones based on safety factors).

Using reliability-based methods for each of these steps makes the approach a very horizontal one. This aspect is reflected in the use of different techniques for each step:

<u>Step 1</u>

Where probabilistic methods are employed, it is important to estimate the variability (in the broad sense of the term), i.e. the distribution of the characteristic parameters of the various elements (devices) subject to the code. Data enabling this variability to be assessed must therefore firstly be collected and secondly be processed probabilistically. It is worth noting that this variability must incorporate not only the intrinsic variability of the studied quantity (e.g. the strength of a weld made using a particular welding process will evidently vary, depending on the geometry of the weld, welding conditions, etc.), but also variability due to imprecise knowledge of the quantity (e.g. inaccurate definitions or measurements). The probabilistic process can be based on any of three methods, depending on the volume and type of data available:

- Conventional frequency-based statistical method,
- Bayesian analysis,
- Structural reliability analysis.

Furthermore, a code generally has a very broad scope, making it impossible to analyze systematically. Representative sample cases must therefore be chosen in order to evaluate the code performance and possibly suggest alternatives to the existing code, whichever method is used.

Step 2

The second step entails setting maximum failure probability targets for the structures, using totally different techniques (e.g. minimum and maximum acceptable risk thresholds, conventional reliability targets, targets differentiated according to the functional consequences of the component's failure, etc.).

Steps 4 and 5

The impact of reliability-based methods on steps 4 and 5 is explained in §4.

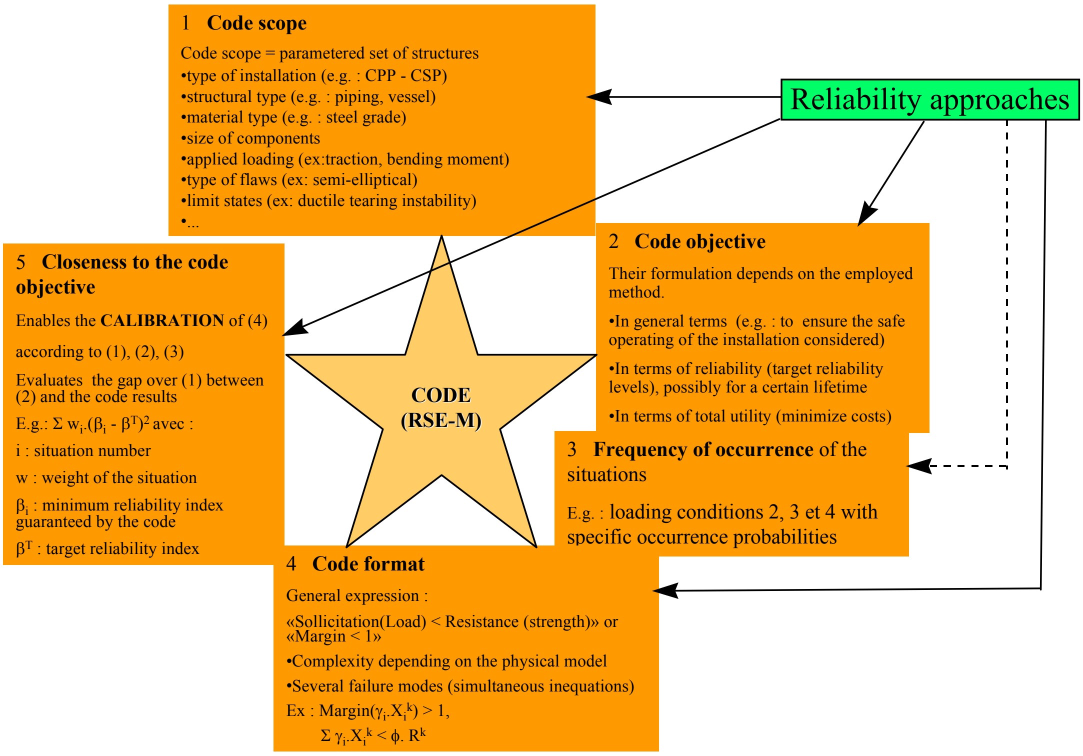

Figure 1 - Steps of the general pro-codification approach

Code Calibration Method Levels

Reliability-based methods can be used at various levels of refinement. There are four different method levels, ranging from the traditional deterministic method to the reliability-based method incorporating specific technical and economic considerations in the form of utility functions.

One common current practice is to use a conventional code format based on pessimistic values, used in conjunction with safety factors (Level 1). This code is calibrated using the reliability-based method (Level 3) on the basis of targets expressed in terms of guaranteed reliability levels.

Furthermore, this reliability-based method can also be used "retroactively" to evaluate the performance of an existing code (rather than calibrating a code in order to obtain given performance levels). Certain technical aspects of this hybrid approach (also known as a semi-probabilistic approach) are detailed below.

Application to existing flaw acceptance criteria for nuclear operating facilities

a) The deterministic basis

The industrial flaw acceptance analyses carried out to prevent ductile tearing initiation rely on the following deterministic criterion :

$$J(\gamma_\sigma \sigma; a; \sigma_0) \leq \frac{J_{0,2}}{\gamma_{J_{0,2}}} \tag{1}$$

J represents the J-integral, $J_{0,2}$ the fracture toughness, a the crack depth, □ the applied stress (proportional to loading), $\square_0$ the yield stress. $\square_{\square}$ and $\square_{J0,2}$ are the safety coefficients applied to stress and fracture toughness.

More precisely, the values of the input parameters of Eq. (1) are characteristic values usually employed in the mechanical analysis. These values are selected as usual values in the pessimistic part of the distribution. Some of them have an explicit statistical meaning : for instance the characteristic value of $J_{0,2}$ is a certain fractile codified in [1] (currently the 16% fractile for pipes). For others the probabilistic calculations will require assumptions.

The computation of the J-integral is based on the simplified (i.e. analytical) methods provided by the RSE-M code (Appendix 5.4) [1]. For instance it is thus possible to calculate the J-integral in a pipe containing a semi-elliptical crack submitted to mechanical loads (in-plane bending and torsion moments, pressure, tension), thermal loads (e.g. shocks) as well as the combination of both type of loads [5]. These analytical methods have been jointly developped by CEA, EDF and FRAMATOME for several years and new options are in progress (longitudinal surface cracks in straight pipes, surface cracks in elbows...). They avoid complex elastic-plastic finite element calculations.

b) The semi-probabilistic approach

As aforementioned the application of the semi-probabilistic approach consists in evaluating the performances of the Level 1 basic approach by Level 3 methods.

More precisely, the first step is to determine for a given component the critical crack size derived from Eq. (1) that becomes an equality. This yields the maximum crack size allowed by the code in the structure. The second step is to compute the failure probability (tearing initiation probability) of the structure containing the critical crack.

Representative structures

To obtain generic evaluations, an important step of the methodology is the selection of representative components for the code scope. Two classes of mechanical components are distinguished from a mechanical point of view, depending on the dominating type of load they are submitted :

- dominating mechanical load ;
- dominating thermal load.

Another significant issue is the mechanical behavior of the component (elastic or plastic).

To ensure a good representation of the whole class of components, the selected representative components will also not be limited to a particular existing component, but will take account of the different components of the class. This is obtained by defining reference variability hypotheses (reference distributions for the input variables of the mechanical model) together with a broad scale of other hypotheses considered in sensitivity studies. All these distributions will come from the available statistical knowledge relating to the variable considered. Three types of situations can be distinguished, involving different treatments :

- if many data are available, the sample size can be considered as sufficient and random distributions can be fitted ; the selection of the best distribution type is a well-known statistical problem, however usual statistical tests and estimators work for the central part of the distribution, and estimating appropriate distribution tails can be difficult ; this difficulty has been identified as a key issue of structural reliability analyses (SRA), in so far as low probabilities are calculated ;
- if little data are available but expert judgment is available, this judgment can be interpreted probabilistically and may provide distribution bounds, parameters or shapes depending on the information available ; it can further be tested over the available (rare) data ;
- if no data is available at all, then the only solution is to derive the variable uncertainty from a modelization of this variable as a function of other variables that can be probabilized.

Code objectives

The complete use of Level 3 method requires the definition of targets in terms of reliability target values. However, this definition is not easy in the frame of the nuclear French industry, although some directions could be explored (for instance the functional consequences of a structural failure). Moreover, this question is significant for calibration of new criteria, but the evaluation of existing codes does not require the definition of a priori objectives. The performances will be more evaluated in term of homogeneity of the reliability levels.

THE SIMPLIFIED PROBABILISTIC APPROACH

This approach has been elaborated during the development of the RSE-M Code Version 1997 [6]. As in the general approach it is necessary to define representative components. For the verification of existing criteria, codes objectives are also expressed more in term of homogeneity of the reliability levels. The differences are as follows :

- Mechanical model : the analytical models mentioned in last paragraph need further simplification ; the new expression of the failure function has to be a product of power functions of the input variables, leading to Eq. (2) :

$$J = C^{ste} \sigma^{n_\sigma} a^{n_a} {\sigma_0}^{n_{\sigma 0}} \tag{2}$$

- Distribution assumptions : all the distributions of random variables are assumed to be lognormal.

This formulation enables to have an explicit link between the reliability index □ and the safety coefficients and the characteristic values :

$$\beta = \frac{n_\sigma \ln(\gamma_\sigma) + \ln(\gamma_{J_{0,2}}) + n_\sigma s_\sigma \Phi^{-1}(f_\sigma) + n_a s_a \Phi^{-1}(f_a) + n_{\sigma_0} s_{\sigma_0} \Phi^{-1}(f_{\sigma 0}) - s_{J_{0,2}} \Phi^{-1}(f_{J_{0,2}})}{\sqrt{[n_\sigma s_\sigma]^2 + [n_a s_a]^2 + [n_{\sigma_0} s_{\sigma_0}]^2 + [s_{J_{0,2}}]^2}} \qquad (3)$$

Where :

- □ is the cumulative distribution function of the standard normal distribution
- $□_X$ is the safety coefficient applied to variable X in the criterion Eq. (1) ;
- f_X is the order of the fractile (for example 0.16 for a 16%-fractile) ;
- n_X is the exponent applied to variable X in Eq. (2)
- s_X is the standard deviation of the logarithm of variable X.

Remember also the relation between the failure probability P_f and the reliability index □ : P_f = □(-□).

As shown in [6] the simplified approach also allows to calculate the stochastic importance factors of each variable. The importance factors are given by the reliability theory [7, 8] ; they are used to determine the influence of each parameter's variability on the estimated probability : if the importance factor of one parameter is low then this parameter can be taken equal to its median value. They are expressed as a percentage ; their sum is equal to 100%. Eq. (4) gives the expression of the importance factor $□_i^2$of variable X_i :

$$\alpha_i^2 = \frac{(n_{Xi} \cdot s_{Xi})^2}{\sum_{j=1}^{N} (n_{Xj} \cdot s_{Xj})^2} \qquad (4)$$

CASE STUDY : COMPARISON OF THE TWO METHODS

Case definition

The study of the tearing initiation risk is carried out on a representative of the class of equipment submitted to dominating mechanical load. This component is a weld joint located in the Main Secondary System and submitted to high load. It has a significant plastic behavior. The mechanical load consists in an overall applied moment combined with internal pressure. The semi-elliptical crack is located on the internal wall of the weld joint. As mentioned in table 1 the regulatory safety factor set considered is ($□_□$ = 1.3 ; $□_{J0,2}$ = 1) : the presented study concern category 2 (normal and upset loading conditions - cf. Table 1). The case input data presented in table 2 are common to the generic and simplified approach.

Table 2 - Case input data

Parameter	**Distribution density**	**mean value**	**standard deviation or coefficient of variation**	**Fractile**
Young's modulus E, MPa	deterministic	190600		
Yield stress $□_0$, MPa	Lognormal	249.54	7.5%	5% (=220)
Fracture toughness $J_{0.2}$, MPa.mm	Lognormal	130	30%	16% (=93)
Exponent of the fracture resistance curve, n_J	deterministic	0.25		
Internal Pressure P, MPa	Lognormal	8.45	10%	84% (= 9.3)
Applied Moment M, kN.m	Lognormal	1071	10%	84% (=1178.2)
Crack depth, a, mm	Lognormal	critical value less 1 mm	1 mm	84%
Half crack length, c, mm		c/a = 3	- -	
Thickness t, mm	deterministic	39.7		
Pipe's internal radius Ri, mm	deterministic	188.9		

Note that for a lognormal random variable the coefficient of variation V_X is almost equal to the logarithmic standard deviation s_X (if $V_X < 0.4$).

The difference between the two approaches basically concerns the mechanical model. The only difference regarding the input data is the distribution of the fracture toughness that can be either lognormal or Weibull in the generic approach.

As aforementioned the mechanical model of the generic approach is that codified in [1]. It uses the true stress-strain curve of the material. In the simplified approach the model is fitted from the RSE-M analytical model to a power-product model. The exponents affecting □, a and $□_y$ depend on the form of the postulated stress-strain curve (cf. Table 3). This curve is assumed to be a Ramberg-Osgood curve, which is not the real curve :

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \left(\frac{\sigma}{\sigma_0}\right)^n \tag{5}$$

The exponent n is taken equal to 6 or to 9.

Table 3 - Parameter exponents in the simplified model

	Plastic behavior n=6	Plastic behavior n=9
n_a	1.53	1.81
$n_□$	5.43	8.23
$n_{□y}$	-3.43	-6.23

Results

The results of the simplified approach directly come from Eq. (3) and (4) without approximation or uncertainty. Those of the generic approach have been obtained by combining in a direct way the general probabilistic code PROBAN [8] with the deterministic code OSTAND [5] containing the equations of the RSE-M mechanical model. In other words, each time the evaluation of J is necessary PROBAN creates the corresponding input file with the simulated values of the different random variables for the deterministic code OSTAND. Then the deterministic code is run. The output parameter J is finally read from the output file of OSTAND. The direct combination is possible thanks to the low computing time of the deterministic calculation. This allowed a verification of the results by using unbiased Crude Monte Carlo simulations. These results were found to be consistent with those provided by the Directional Simulation Method, which was therefore selected for the other calculations. The probability of initiation P_f is given in Table 4 as well as the importance factors. For the simulation results, the coefficient of variation of the estimated probability, provided by the simulation, is given in parentheses. The given values allowed to limit the number of directional simulations to 500.

Table 4 - Probability of ductile tearing initiation and importance factors for the two approaches

	Simplified approach		Generic approach		
	n=6	n=9	J_{02} Lognormal 500 Dir. Sim.	J_{02} Lognormal Monte Carlo 6 982 178 sim.	J_{02} Weibull 500 Dir. Sim.
P_f	$2.4\ 10^{-5}$	$1.5\ 10^{-5}$	$8.\ 10^{-6}$ (*0.17*)	$1.08\ 10^{-5}$ (*0.12*)	$4.9\ 10^{-5}$ (0.13)
$□^2_a$	17.2%	11.7%	5.4%	the calculation of importance factors with crude Monte Carlo simulation is not possible	2.1%
$□^2_□$	54.1%	60.7%	50.6%		39.9%
$□^2_{□y}$	12.2%	19.6%	18.3%		17.4%
$□^2_{J02}$	16.5%	8.1%	25.4%		40.4%

It can be noticed that :

- the simplified and generic approaches give close results in terms of probability ;
- the use of Weibull distribution for the material property J_{02} does not affect the order of magnitude of P_f, but increases P_f as well as the importance of J_{02}. This is due to the fact that the lower distribution tail of the Weibull distribution is more important than that of the lognormal distribution : for instance for the same distribution parameters (mean=130, coefficient of variation=0.3, lower bound=0), the 5% fractile of the lognormal is 76.8 while 64.7 for the Weibull ;
- slight differences appear in the evaluation of the importance factors : the role of load is higher in the simplified approach

Therefore it can be concluded from this example that :

- the simplified method gives robust results (simplification of the model, degree of plasticity, change in distribution)
- extensive use of the simplified method would require further verification by exact calculations on the case considered.

CONCLUSION

The prevention of the fast fracture damage of the mechanical equipments important for the safety of nuclear islands of the French PWR relies on deterministic rules. These rules include flaw acceptance criteria involving safety factors applied to characteristic values (implicit margins) of the physical variables. A reference overall safety factor applied to loading has been adopted in the new « Operation » Decree issued by the French Nuclear Safety Authority.

However this factor is valid for a specific reference case, and to cover the whole scope of the Decree, other sets of safety factors are currently under application in the industrial analyses with the agreement of the Safety Authority. These factors are distributed across the two main physical parameters and they have partly been based on a semi-probabilistic approach.

After presenting the generic probabilistic pro-codification approach this paper has described its application to the evaluation of the performances of the existing regulatory flaw acceptance criteria. This application can be carried out in a realistic manner or in a more simplified one. These two approaches are applied to representative mechanical equipments. Their results are consistent. So the simplified approach works satisfactorily but requires further verification for extensive use.

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