A methodology for measuring the difficulty of nuclear safety culture and safety management factors

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Abstract: This study is aimed at developing an in-depth safety culture analysis tool for detailed analysis by safety culture attribute and a methodology to promote mutual understanding of safety culture for each organization. This method can be used for appropriate resource allocation when establishing a response strategy to improve the organization's safety culture weaknesses that can be obtained through other safety culture evaluation results. Meaningful results can be derived by comparing the weight of each factor contributing to the difficulty of safety culture by reflecting the perception bias of respondents about the difficulty of safety culture. For example, it can be used to elicit differences in perceptions of safety culture that exist between regulatory bodies and operating organizations, or to elicit differences in perceptions of safety culture based on location within an organization. The concept of difficulty and quantification method of safety culture characteristic elements proposed in this study were used in F-D matrix analysis for in-depth analysis of safety culture. In this paper, the concept of difficulty of safety culture characteristic elements is defined and quantification methods are introduced.

1. INTRODUCTION

In safety-critical industries, continuous efforts have been made to achieve a higher level of safety. Numerous studies focus on safety management methods for higher safety performance. Nuclear industry is one of the safety-critical fields and has a very complex structure. In such a complex system, a systematic approach to safety is required for effective safety management. Therefore, many organizations strive to enhance safety management capabilities by establishing and improving safety management systems. A safety management system has two main functions: a function to identify and prepare for potential risks related to hazards that an organization can have, and one to improve it through feedback on system performance. Since the culture for safety of an organization affects all activities within the organization, it has a close influence on the performance of the safety management system. Therefore, organizations have an obligation to put an enormous effort into fostering and improving safety culture. Safety culture maturity and safety management competency can improve through a systematic approach and analysis from various viewpoints. This paper introduces a method approaching safety-related elements with the concept of difficulty. This paper describes the methodology for evaluating the difficulty.

2. BACKGROUND

2.1. Safety Culture and Safety Management

Safety culture is a concept that began to attract attention after the Chernobyl nuclear accident in 1986. There are various definitions and models describing safety culture, but IAEA's and US NRC's definitions are representative in the nuclear field. IAEA defines (nuclear) safety culture as "a collection of characteristics and attitudes of organizations and individuals who pay attention to nuclear safety issues commensurate with the importance of the issues as the top priority value" [1], while the NRC defines it as "the core values and behaviors resulting from the collective promise of management and individuals who emphasize safety rather than objective goals to ensure the protection of humans and the environment" [2]. The concept of safety culture has become commonly introduced in many other

industries. Combining various definitions, the common conceptual parts of safety culture are 'the way a group manages safety' or 'the attitudes, beliefs, perceptions, and values shared by workers regarding safety.' James Reason suggested that good safety culture has five key elements: informed, reporting, learning, flexible, and just culture [3]. These factors are often considered subcultures of safety culture or indicators of good safety culture. There are various attempts to measure or evaluate the maturity of a safety culture based on the belief that a good safety culture leads to enhanced safety performance. Each takes different methods, but there is a consensus that an organization should comprehensively consider all factors affecting safety culture within the organization since safety culture has an inherent character that cannot be measured or evaluated directly.

Safety management is a term that subsumes all activities (e.g., planning, organization, management, supervision) to effectively achieve a high level of safety performance. In other words, safety management is to manage all activities to achieve high quality of all activities related to safety and to promote a highly developed safety culture. For effective safety management, it is necessary to establish a well-developed safety management system, and the larger the organization, the more essential the systematic safety management system. It is said that the success of a safety management system depends on positive safety culture and that the safety management system plays a role in providing an organizational methodology to produce and build a positive safety culture, which James Reason suggested as A well -developed SMS can therefore serve as an accelerator of Safety Culture [3-5]. As such, safety culture, safety management, and safety management system have a very close relationship, and components and principles often show similar forms.

2.2. Degree of Difficulty

The dictionary meaning of "Difficulty" is "the state or quality of being hard to do or to understand; The effort that something involves" or "how hard something is" or "a condition or state of affairs almost beyond one's ability to deal with and requiring great effort to bear or overcome [6]." The concept of difficulty started from such definitions. In other words, difficulty means the resource(s) and ability involved, the degree of difficulty represents the extent of difficulty (i.e., the qualitative level of required ability and the amount of effort or resource involved). It is possible to quantify the amount of effort to show or improve safety culture by evaluating the degree of difficulty of safety culture. The quantified value itself is not meaningful, but it can suggest a standard for relative comparison within multiple factors. In other words, the difficulty of safety culture should not be evaluated by considering 'safety culture' as a separable thing, but evaluated the components derived by dismantling concepts related to safety culture. For example, the latest safety culture model of the IAEA consists of 10 traits and 43 attributes [7]. Evaluating the difficulty of the IAEA safety culture model means evaluating the difficulty of 10 traits (i.e., at the trait level) or evaluating the difficulty of 43 attributes (i.e., at the attribute level). On the other hand, if an organization has established a safety culture improvement strategy, the difficulty of detailed strategies can be evaluated. Since this quantified difficulty reflects the total amount of resources required to promote each strategy, the difficulty score can be referred to when allocating limited resources. Likewise, the difficulty of safety management can be measured by decomposing it into elements necessary for safety management, or by evaluating various comparable safety management strategies. This paper focused more on the difficulty evaluation of safety culture, and the next chapter describes the methodology of difficulty evaluation.

3. DIFFICULTY EVALUATION METHODOLOGY

The first step of evaluating the difficulty is deciding the subjects according to the purpose of the evaluation. For example, if the purpose is to identify any potential problem causal factors among various factors (e.g., multiple safety management principles or safety culture principles), the difficulty of factors can be compared. The evaluation process of safety culture (or detailed components of safety culture, etc.) consists of qualitative evaluation and quantification of the results. It is helpful to establish criteria to ensure consistency across multiple evaluations. Therefore, qualitative and quantitative evaluation of difficulty can be done after the process of developing standards and criteria.

3.1. Evaluation Criteria Development

The evaluation criteria of difficulty can be developed by specifying factors for qualitative evaluation and assigning weights for quantification. Qualitative evaluation of difficulty is the process of deriving the requirements that something accompanies. That is, all factors that can contribute to the difficulty are derived and systematized and can be used as a qualitative evaluation standard for difficulty. According to the definition of difficulty, the entire space of difficulty is divided into two mutually orthogonal axes, the resource dimension, and the competency dimension (Figure 1). The resource dimension reflects the quantitative aspect of the difficulty, and the competency dimension reflects the qualitative aspect of the difficulty. In detail, the resource dimension reflects the required amount of tangible/intangible resources, that is, the amount of time required, or energy consumed, and the amount of material resource (i.e., related to cost). It was considered that the greater the resource requirement, the greater the obstacle, that is, the greater the degree of difficulty. On the other hand, the competency dimension reflects the capabilities to be possessed and their level. It will be more difficult when a variety of skills are required, or a higher level of skill is required. Each factor is preferably independent of the other, and the more detailed it is, the more precise the criterion can be. However, if the number of factors is too large, excessive effort may be consumed in the evaluation process. To avoid this, it is necessary to develop a standard of an appropriate scale (i.e., the number of criteria and the number of layers in the stratified structure) according to the purpose of use.

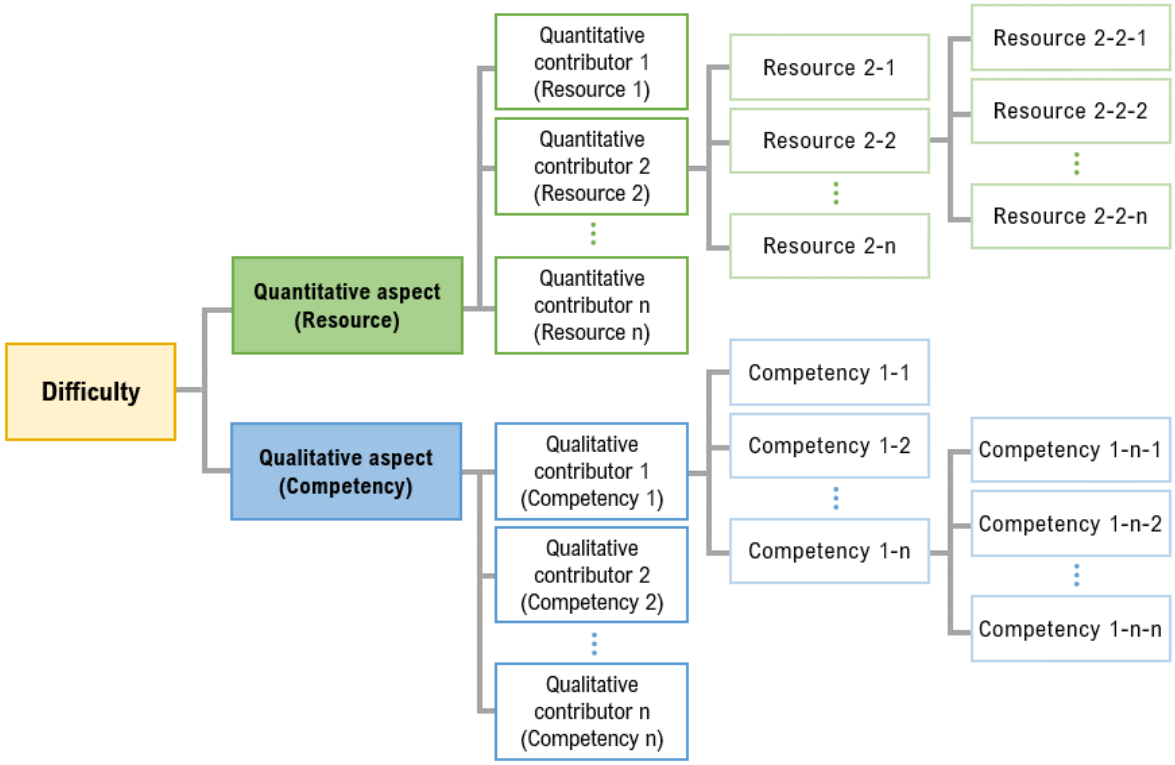

Figure 1: Stratified Qualitative Criteria for Difficulty Evaluation

In order to quantify the qualitative evaluation result, a weight should be assigned to each element. Since the qualitative evaluation model is layered, weights can be assigned through the analytic hierarchy process (AHP) analysis method [8]. AHP is a widely used method in multi-factor decision making, and it is a method that can provide consistent evaluation and quantitative weighting when prioritizing multiple factors. Analysts only need to qualitatively evaluate the relative importance through the pairwise comparison. Using the AHP method, it is possible to check whether there is a contradiction between responses by calculating the consistency index based on the response results. AHP analysis can be performed by experts who know the relevant field well and those engaged in related work. Various scales can be considered in the converting process from the pairwise comparison response results into weights, and the scales shown in the Table 1 have been proposed.

Table 1: Judgement scales for the AHP method

Scale type	Mathematical description	Parameters	Approximate scale values
Linear [8]	$s = x$	$x = \{1, 2, \dots, 9\}$	$1; 2; 3; 4;$ $5; 6; 7; 8; 9$
Power [9]	$s = x^2$	$x = \{1, 2, \dots, 9\}$	$1; 4; 9; 16; 25;$ $36; 49; 64; 81$
Root square [9]	$s = \sqrt{x}$	$x = \{1, 2, \dots, 9\}$	$1; \sqrt{2}; \sqrt{3}; 2; \sqrt{5};$ $\sqrt{6}; \sqrt{7}; \sqrt{8}; 3$
Geometric [10]	$s = 2^{x-1}$	$x = \{1, 2, \dots, 9\}$	$1; 2; 4; 8; 16;$ $32; 64; 128; 256$
Inverse linear [11]	$s = \frac{9}{10 - x}$	$x = \{1, 2, \dots, 9\}$	$1; 1.13; 1.29; 1.5;$ $1.8; 2.25; 3; 4.5; 9$
Asymptotical [12]	$s = \tanh^{-1}\frac{\sqrt{3}(x-1)}{14}$	$x = \{1, 2, \dots, 9\}$	$0; 0.12; 0.24; 0.36; 0.46;$ $0.55; 0.63; 0.7; 0.76$
Balanced [13]	$s = \frac{w}{1 - w}$	$w =$ $\{0.5, 0.55, 0.6, \dots, 9\}$	$1; 1.22; 1.5; 1.86;$ $2.33; 4; 5.67; 9$
Logarithmic [14]	$s = \log_2(x + 1)$	$x = \{1, 2, \dots, 9\}$	$1; 1.58; 2; 2.2; 2.58;$ $2.81; 3; 3.17; 3.32$

3.2. Qualitative Evaluation

Qualitatively evaluating the difficulty level of evaluation objects is a process of identifying difficulty contributing factors related to each object. Allocate evaluation targets and evaluation criteria to rows and columns, respectively. For each subject, check the applicable (i.e., which the subject involves) criteria. If the purpose of a simple evaluation is to evaluate, only the relevance is considered (Table 2), and for a detailed analysis, the degree of relation is expressed on a scale such as high, medium, low, etc. (Table 3).

Table 2: Example of Qualitative Evaluation Table for Simplicity

	Criterion 1	Criterion 2	…	Criterion m
Candidate 1	O	X	…	O
Candidate 2	X	X	…	O
…	…	…	…	…
Candidate n	O	O	…	X

Table 3: Example of Qualitative Evaluation Table for Detailedness

	Criterion 1	Criterion 2	…	Criterion m
Candidate 1	High	None	…	Medium-high
Candidate 2	None	None	…	Medium
…	…	…	…	…
Candidate n	Low	High	…	None

3.3. Quantitative Evaluation

Quantitative evaluation is calculated using the weight assigned to each element based on the qualitative evaluation result. The qualitative evaluation result is converted into a scale value, and the quantitative criterion (weight determined through AHP) of the criterion is reflected.

$$D_i = \sum_{k=1}^{m} s_{ik} \cdot w_k \tag{1}$$

The degree of difficulty, D_i of the i-th candidate is calculated as in Equation (1). s denotes the scale value corresponding to the qualitative evaluation result shown in the table, and w denotes the weight of the criterion determined through AHP. For simple analysis, s will be 1 or 0, and for detailed analysis purposes, it represents the scale weight (discrete scale is recommended but can be continuous if the precise analysis is required or possible).

The quantified difficulty level of each candidate can be used as it is, and the standardized degree of difficulty can derive a difference in perception of safety culture or safety management by layer. In order to derive recognition differences according to hierarchies in the organization (e.g., position, tenure, department, etc.), a quantitative standard preparation process (difficulty contributor weighting through AHP) is performed for each hierarchical level, and a weight set $w = \{w_1, \ldots, w_m\}$ should be derived for each layer. By comparing the results of d with different w_s reflected, it is possible to grasp the detailed elements of safety culture or safety management that each layer perceives as difficult or easy.

$$D_{i,normarlized} = 0.5 + \left(D_i - \frac{\sum_{k=1}^{n} D_k}{n} \right) \times \left(\frac{\sum_{k}^{n} \left(D_k - \frac{\sum_{j=1}^{n} D_j}{n} \right)^2}{n} \times 100 \right)^{-\frac{1}{2}} \quad (2)$$

4. CASE STUDY

In the case study, forty-three attributes of the IAEA harmonized safety culture (HSC) model are used as parameters (i.e., evaluation subjects) [7]. This model summarizes various characteristics of an organization with good safety culture into ten traits and forty-three attributes (Table 4). This model suggests that organizations with good safety culture exhibit the characteristics of good safety management. According to the definition of this model, the difficulty of this attribute means the extent of resources or the level of capability that an organization needs to put in to have the characteristics described by the attribute. From the perspective of workers, when fulfilling their responsibilities related to safety within the organization, it becomes a burden or difficulty in complying with practice guidelines or regulations related to the attribute.

Table 4: Harmonized Safety Culture Model – 10 Traits and 43 Attributes [7]

Traits	Attributes		Traits	Attributes	
IR Individual Responsibility	IR.1	Adherence	**DM** Decision-Making	DM.1	Systemic Approach
	IR.2	Ownership		DM.2	Conservative Approach
	IR.3	Collaboration		DM.3	Clear Responsibility
				DM.4	Resilience
QA Questioning Attitude	QA.1	Recognize Unique Risks	**WE** Work Environment	WE.1	Respect is Evident
	QA.2	Avoid Complacency		WE.2	Opinions are Valued
	QA.3	Question Uncertainty		WE.3	Trust is Cultivated
	QA.4	Recognize and Question Assumption		WE.4	Conflicts are Resolved
				WE.5	Facilities Reflect Respect
CO Communication	CO.1	Free flow of information	**CL** Continuous Learning	CL.1	Constant Examination
	CO.2	Transparency		CL.2	Learning from Experience
	CO.3	Reasons for Decisions		CL.3	Training
	CO.4	Expectations		CL.4	Leadership Development
	CO.5	Workplace Communication		CL.5	Benchmarking
LR Leader Responsibility	LR.1	Strategic Alignment	**PI** Problem Identification and Resolution	PI.1	Identification
	LR.2	Leader Behavior		PI.2	Evaluation
	LR.3	Employee Engagement		PI.3	Resolution
	LR.4	Resources		PI.4	Trending

	LR.5	Field Presence	**RC** Raising Concerns	RC.1	Supportive Policies are Implemented
	LR.6	Rewards and Sanctions		RC.2	Confidentiality is Possible
	LR.7	Change Management	**WP** Work Planning	WP.1	Work Management
	LR.8	Authorities, Roles, and Responsibilities		WP.2	Safety Margins
				WP.3	Documentation and Procedures

4.1. Evaluation Criteria Development

Through previous research, a stratification model of factors contributing to the difficulty was developed by deriving and screening all difficult factors that may accompany the process of complying with safety culture principles or reinforcing the level (Figure 2). Since the presented example is a model developed as a qualitative standard for evaluating the difficulty of safety culture, technical aspects are not subdivided. Since safety management can be affected more by technical aspects than safety culture, more precise results can be derived if a model is constructed and utilized in which technical aspects are subdivided. To give weight to the Difficulty contributors, AHP was performed by experts in human factors and safety culture in the nuclear field.

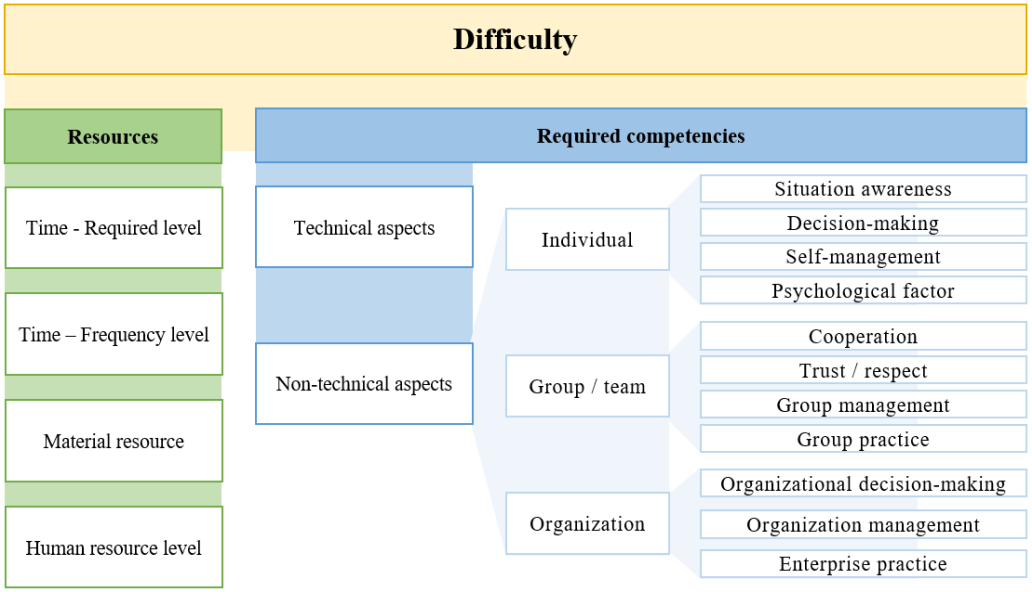

Figure 2: The Difficulty Contributor Hierarchical Model (DCHM)

4.2. Evaluation Result

The results of quantifying all responses based on integrated weights are shown in the Figure 3. By examining the ranking of the elements based on the difficulty in this way, it is possible to predict which areas are likely to cause frequent problems. In order to achieve high safety performance, it is necessary to design multiple safety barriers that respond to expected risks. The degree of difficulty is not an indicator that directly reveals risk but serves as a kind of leading indicator for areas where problems may occur. In our previous study, in order to examine whether difficulty can act as a leading indicator, we analyzed safety-related events and derived the frequency of factors contributing to the event, and as a result, it was shown that there is a significant correlation between frequency and difficulty.

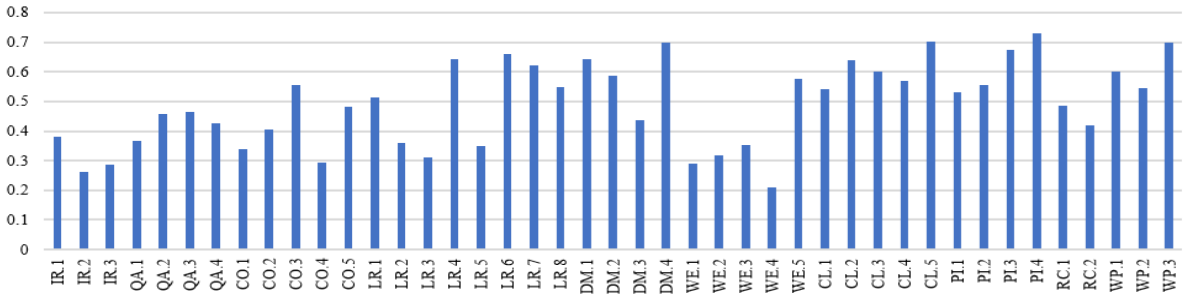

Figure 3: Integrated Degree of Difficulty for 43 Safety Culture Attributes

4.3. Comparative Analysis of Evaluation Results

Table 5 shows comparing each AHP response result based on the respondent's class to create a weight set for each class, and to compare the reflected results. The color of a cell indicates the relative size of the corresponding row element in each column. By visualizing the relative size in this way, it is possible to intuitively identify the part where the difference appears. The last column indicates the variance of the trait's degree of difficulty value, and this value indicates the degree of discrepancy between response results. The Trait with the greatest degree of discrepancy is RC, and the response result of Group 1 means that the raising concern recognizes that it is relatively difficult (orange), but the response result of Group 4 confirms that it is perceived as easy (green). can for the improvement of safety culture and effective safety management, trust and respect for each other are essential, and smooth communication must take place. Knowing the difference in perception of each other will help us understand and respect each other. Resolving this perception gap can help to build and improve the organization's safety culture.

Table 5: Comparison of Safety Culture Perception

Traits	Group 1	Group 2	Group 3	Group 4	Inconsistency
IR	0.27140	0.28406	0.37149	0.44994	0.030481
QA	0.31650	0.44699	0.48179	0.51620	0.045531
CO	0.39555	0.41029	0.38278	0.49248	0.019688
LR	0.49096	0.49499	0.51433	0.52032	0.017438
DM	0.52784	0.60963	0.59687	0.64551	0.041371
WE	0.33655	0.28841	0.32612	0.43016	0.020215
CL	0.57968	0.63803	0.64360	0.58249	0.030620
PI	0.56685	0.61560	0.66324	0.65110	0.011703
RC	0.55094	0.43637	0.39590	0.41802	0.083606
WP	0.55584	0.62401	0.63772	0.66567	0.019351

5. CONCLUSION

The purpose of this study is to develop an in-depth safety culture analysis tool for a detailed analysis of safety culture attributes and to present a methodology to promote mutual understanding among stakeholders. Since the frequency of problems can increase as the difficulty increases, the difficulty level can serve as a kind of leading indicator for the potential risk of an organization. This method can be used for appropriate resource allocation when establishing a response strategy to improve the organization's safety culture weaknesses that can be obtained through other safety culture evaluation results in the future. And by comparing the weight of each factor contributing to the difficulty of safety culture by reflecting the perception bias of the respondents on the difficulty of safety culture, meaningful results can be derived. For example, it can be used to elicit differences in perceptions of safety culture that exist between regulatory bodies and operating organizations or to elicit differences in perceptions of a safety culture based on location within an organization.

Nevertheless, this study has the following limitations. First, the parameters used in the case study do not represent the same level from an organizational point of view. Therefore, the qualitative evaluation results may vary somewhat depending on the analyst's point of view. To overcome this, the analyst who performed the qualitative evaluation tried to evaluate the same person with a consistent standard. Nevertheless, analyzing the difficulty of safety culture and safety management principles or elements can ultimately contribute to effective safety management, which is expected to lead to reinforcement of safety culture.

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