# Evaluation of the Nuclear Emergency Response Equipment System Based on AHD Fuzzy Comprehensive Evaluation Method

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**Abstract: In light of the current circumstances and the functional missions entrusted to various departments, this study evaluates the capability requirements for performing nuclear emergency response tasks. By employing the AHD fuzzy comprehensive evaluation method, we conduct a thorough evaluation of the anticipated equipment capabilities, thereby providing pertinent foundations for future equipment development. Taking as a reference the equipment system of a Level 3 nuclear emergency response force at a specific nuclear power plant, we meticulously analyzed we analyzed the current status of the equipment system and its associated capabilities. An indicator system was constructed, encompassing command and support, radiation monitoring, security alertness, decontamination, and personnel protection. Subsequently, targeted evaluations were conducted to expedite the establishment of a nuclear emergency equipment system that is adaptable to information warfare and meets mission requirements. This approach aims to facilitate the timely development of nuclear emergency capabilities, ensuring they fulfill their intended roles effectively.**

**Keywords: Nuclear Emergency; Equipment System; Fuzzy Comprehensive Evaluation Method; Evaluation Indicators; Evaluation Process**

## 1. Introduction

The capability for nuclear emergency response must fulfill the demands of joint operations, as its efficacy is crucial to the success or failure of such responses, underscoring its paramount significance [1-4]. The construction of a nuclear emergency equipment system must fundamentally hinge on the enhancement of capabilities; thus, evaluating the anticipated equipment capabilities is an essential preliminary condition. Given that evaluations of the equipment system often exhibit ambiguous attributes, the focus of evaluation rests upon a multitude of relevant factors that must be considered. The adoption of fuzzy comprehensive evaluation facilitates the consideration of these pertinent factors related to the subject of evaluation, thereby enabling a holistic evaluation of the subject as a whole [5-8]. By applying the principles of fuzzy transformation and the maximum membership degree principle, this approach seeks to explore pathways and methodologies for equipment construction grounded in theoretical guidance and a step-by-step, point-to-plane strategy. This aims to accurately identify the bottlenecks and critical points in the construction of the equipment system, clarify developmental priorities, enumerate relevant measures and considerations, and ultimately provide theoretical guidance for subsequent equipment development.

## 2. Analysis and Construction of Evaluation Indicators for Nuclear Emergency Capabilities of Relevant Departments

The anticipated capabilities of the nuclear emergency equipment system reflect the comprehensive qualities manifested by the forces in efficiently executing the nuclear emergency tasks assigned by higher authorities within the context of joint operations [9]. Through an analysis of the current state of equipment construction, it can be concluded that the units have preliminarily established capabilities in command and support, radiation monitoring, security alertness, decontamination, and personnel protection. This serves as the foundation for constructing a scientifically sound and logically coherent indicator system for anticipated capabilities, as illustrated in Table 1.

**Table 1. Capability Indicators for Nuclear Emergency Equipment System Construction**

| | Primary Indicators | Secondary Indicators |
|---|---|---|
| Capability of Nuclear Emergency Equipment System Construction | Command and Support Capability (A1) | Nuclear Emergency Command Capability (A11) |
| | | Nuclear Emergency Support Capability (A12) |
| | Radiation Monitoring Capability (A2) | Environmental Monitoring Capability (A21) |
| | | Data Transmission Capability (A22) |
| | Security Alertness Capability (A3) | Suppression Capability (A31) |
| | | Unmanned Mechanical Operations Capability (A32) |
| | Decontamination Capability (A4) | Decontamination Capability (A41) |
| | | Recovery Capability (A42) |
| | Personnel Protection Capability (A5) | Individual Emergency Action Protection Capability (A51) |
| | | Personnel Respiratory Support Capability (A52) |
| | | Monitoring Capability for Vital Signs and Location (A53) |

## 2.1 Command and Support Capability

The ability to rapidly establish emergency communication systems at nuclear incident sites ensures seamless communication and interaction between task units and command centers, enabling timely awareness of mission execution status. This capability encompasses comprehensive support functions for communication command, video surveillance, environmental meteorology, and safety protection at nuclear accident sites. Additionally, it includes on-site rapid maintenance and component replacement for nuclear emergency equipment, as well as the provision of collective protection functions such as water, electricity, gas, and vehicle support at nuclear accident locations [10].

## 2.2 Radiation Monitoring Capability

Radiation monitoring equipment consists of various systems, including airborne radiation monitoring systems, vehicle-mounted radiation monitoring systems, fixed-point radiation monitoring systems, portal radiation detection devices, portable radiation monitoring equipment, and remote radiation monitoring devices [11]. Through the utilization of such equipment, duty units are able to swiftly establish nuclear observation monitoring posts and conduct basic observations and evaluations using handheld radiation detectors. When hazards reach warning threshold levels, prompt reporting occurs, providing essential data support for upper-level decision-making.

## 2.3 Security Alertness Capability

In addition to standard containment equipment such as isolation fences, unmanned systems including drones and robots are increasingly deployed. Leveraging the aforementioned equipment, initial rescue forces promptly classify the nuclear power plant and its periphery into core, control, and safety zones based on contamination levels. They implement security alertness at key entry and exit points of the core zone, with emphasis on monitoring major pathways surrounding the control zone, strictly prohibiting entry by individuals not wearing protective gear or unauthorized personnel. They also prevent the exit of individuals who have not undergone decontamination and isolate and verify any suspicious sources of contamination [12]. Furthermore, evacuation routes are established between the control and safety zones, facilitating the relocation of non-essential personnel within the control zone to designated safe areas in cooperation with local rescue teams. Subsequent support units, on the basis of external security containment, will expand the monitoring perimeter of the control zone according to contamination levels and directives from higher authorities.

## 2.4 Decontamination Capability

The decontamination equipment designated for nuclear emergencies primarily comprises decontamination tools, including personnel decontamination systems and decontamination systems for weaponry and equipment. Additionally, nuclear recovery equipment includes portable X-ray machines, liquid spraying and cutting devices, and recovery containers.

## 2.5 Personnel Protection Capability

Equipment such as multifunctional protective suits against nuclear radiation, self-sufficient air supply systems, and emergency visual and auditory alarm systems provide critical support for personnel protection during nuclear emergencies. This equipment can generate three principal capabilities: basic personal protection, dose monitoring, and comprehensive protection. Basic protection is primarily achieved through the utilization of individual protective clothing and masks along with the ingestion of stable iodine tablets [13]. Individual dose monitoring capability is facilitated by personnel using personal dosimeters for real-time and cumulative monitoring. Comprehensive personal protection includes wearing radiation protection suits, with the capacity to operate safely for one hour in the presence of low-energy X-rays and gamma radiation.

# 3. Evaluation Process Based on Multi-Level Fuzzy Comprehensive Evaluation

The Analytic Hierarchy Process (AHP) serves as a quintessential method for determining the weights of evaluation indicators. This approach guarantees scientific rigor and objectivity through quantitative weighting, while simultaneously incorporating qualitative analyses from experts to ensure practical relevance, thus affirming the results' scientific validity and reliability.

## 3.1 Construction of the Multi-Level Fuzzy Comprehensive Evaluation Model

Based on the expected capability indicator system for nuclear emergency equipment, multi-level fuzziness was employed to evaluate the anticipated capacities of such equipment, as detailed in the following evaluation process:

3.1.1 Establishment of the factor set $U$

The factor set was segmented according to different natures into subsets $U_i$, resulting in mutually exclusive sub-factors. The overall factor set $U$ was defined as:

$$U=\{U_1,U_2,U_3,\cdots,U_i,\cdots,U_n\},(i=1,2,3,\cdots,n) \quad (1)$$

Where, $U_i$ represents the *i*-th element of the primary indicators, and $U_{im}$ is determined by the m-th element of the secondary indicators:

$$U_i=\{U_{i1},U_{i2},U_{i3},\cdots,U_{ij},\cdots,U_{im}\},(j=1,2,3,\cdots,m) \quad (2)$$

3.1.2 Establishment of weights

The importance of each factor was evaluated within its respective level to determine its weight. The constructed weights are as follows:

First-Level Indicator Weights:

$$W=(W_1 \quad W_2 \quad W_3 \quad \cdots \quad W_i \quad \cdots \quad W_n),(i=1,2,3,\cdots,n) \quad (3)$$

Second-Level Indicator Weights:

$$W_i=(W_{i1} \quad W_{i2} \quad W_{i3} \quad \cdots \quad W_{ij} \quad \cdots \quad W_{im}),(j=1,2,3,\cdots,m) \quad (4)$$

3.1.3 Determination of the evaluation set $V$

The evaluation set refers to the collection of evaluations made for each subject under evaluation. It encompasses all evaluation outcomes, with a singular choice for the evaluated entity, independent of the hierarchical levels being evaluated.

$$V=\{V_1,V_2,V_3,\cdots,V_p\},(p=1,2,3,\cdots) \quad (5)$$

To facilitate processing, the range of values for the number of evaluation levels $p$ is generally set between [3,7]. A value of $p$ that is too low diminishes the quality of the fuzzy comprehensive evaluation, while a value that is too high leads to semantic distinctions that are difficult to discern, complicating the judgment of the evaluation object's classification. Typically, five fuzzy levels are employed to represent the evaluation set $V$: "very poor", "poor", "fair", "good", and "excellent".

3.1.4 Determination of the membership degree matrix

For each individual factor $U_i$ in the factor set $U$ (where $i$=1,2,…,m), a singular evaluation was conducted. Upon determining the membership degree $r_{ij}$ for each factor $U_i$ with respect to the evaluation outcome, the individual evaluation set $r_i=(r_{i1},r_{i2},\cdots r_{in}),(i=1,2,3,\cdots,m)$ for the *i*-th factor Ui was established as a fuzzy subset within the evaluation result set V. Thus, by arranging the m individual evaluation sets as rows, we constructed the overall evaluation matrix:

$$R=\begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & \cdots & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{pmatrix} \quad (6)$$

Where, $r_{ij}$ denotes the membership degree of the factor in question.

3.1.5 First-Level fuzzy comprehensive evaluation

The evaluations of secondary indicators concerning primary indicators are regarded as first-level fuzzy comprehensive evaluations. Since the factors associated with the primary indicators determine and govern those of the secondary indicators, the multifactor evaluation results of the primary indicators will be influenced by the evaluations of the various factors within the secondary indicators. Let $R_i$ denote the single-factor evaluation matrix of the secondary indicators:

$$R_i = \begin{pmatrix} r_{i11} & r_{i12} & \cdots & r_{i1n} \\ r_{i21} & r_{i22} & \cdots & r_{i2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{in1} & r_{in2} & \cdots & r_{inn} \end{pmatrix} \quad (7)$$

The number of entries j in $U_{ij}$ determines the number of rows in the matrix $R_i$. The first-level fuzzy comprehensive evaluation vector $B_i$ is represented as follows:

$$B_i = W_i \circ R_i = \begin{pmatrix} W_{i1} & W_{i2} & \cdots & W_{in} \end{pmatrix} \circ \begin{pmatrix} r_{i11} & r_{i12} & \cdots & r_{i1n} \\ r_{i21} & r_{i22} & \cdots & r_{i2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{in1} & r_{in2} & \cdots & r_{inn} \end{pmatrix} = \begin{pmatrix} b_{i1} & b_{i2} & \cdots & b_{in} \end{pmatrix} \quad (8)$$

where "∘" symbolizes the fuzzy synthesis operation, which can also be executed using matrix dot multiplication in this context.

3.1.6 Fuzzy Comprehensive Evaluation

The evaluation of the target layer concerning the primary indicators is regarded as the fuzzy comprehensive evaluation. Following the completion of the first-level fuzzy comprehensive evaluation, it is essential to base the calculations of the comprehensive membership degree vector on the results obtained at this first level. Let $Q$ denote the comprehensive membership degree vector, expressed as:

$$Q = W \circ \begin{pmatrix} B_1 \\ B_2 \\ \vdots \\ B_m \end{pmatrix} \quad (9)$$

Where, $P$ represents the rating vector for feedback, yielding the evaluation value E:

$$E = P \cdot Q^T \quad (10)$$

## 3.2 Application of the Fuzzy Comprehensive Evaluation Model

Taking the mobile support force of a certain nuclear power plant—specifically, a chemical defense unit—as an example, a multi-level fuzzy comprehensive evaluation method was employed to evaluate its anticipated capabilities in nuclear emergency equipment. Other forces may also utilize this theoretical framework for their evaluations.

3.2.1 Calculation of the weights for the evaluation indicator system

The weights of the indicators at each level were computed according to the steps outlined in the AHP. A survey questionnaire concerning indicator weights was distributed to ten experts, who evaluated the relative importance of the indicators in pairs. Upon collection, the data from the questionnaires was organized and analyzed, resulting in the calculation of the weights for the primary evaluation indicators, thus obtaining the judgment matrix:

$$A = \begin{pmatrix} 1 & 3 & 2 & 2 & 7 \\ 1/3 & 1 & 1/2 & 1/2 & 1/3 \\ 1/2 & 2 & 1 & 1/3 & 4 \\ 1/2 & 2 & 3 & 1 & 2 \\ 1/7 & 3 & 1/4 & 1/2 & 1 \end{pmatrix} \quad (11)$$

The vector $\overline{W}_i$ was then normalized:

$$W = \frac{\overline{W}_i}{\sum_{i=1}^{n} \overline{W}_i} = \begin{pmatrix} 0.407 \\ 0.081 \\ 0.177 \\ 0.240 \\ 0.093 \end{pmatrix}^T \quad (12)$$

and the maximum eigenvalue $\lambda_{\max}$ of the matrix was calculated to conduct a consistency check:

$$\lambda_{\max} = \frac{\sum_{i=1}^{n} AW_i}{nW_i} \quad (13)$$

With a calculated $C_R$ value $\leq 0.1$, which meets the consistency check criteria, this matrix can be considered consistent. Thus, the weights of the primary indicators are presented in Table 2.

**Table 2. Weights of the Target Layer Indicators**

| Indicator | A1 | A2 | A3 | A4 | A5 |
|---|---|---|---|---|---|
| Weight | 0.407 | 0.081 | 0.177 | 0.240 | 0.093 |

The steps for the calculation of the weights for the secondary indicators follow a similar methodology.

Upon analysis of the results from the weight calculations, the weights for the primary indicators $W$ are determined as follows:

$$W = \begin{pmatrix} 0.407 \\ 0.081 \\ 0.177 \\ 0.240 \\ 0.093 \end{pmatrix}^T \quad (14)$$

Consequently, the evaluation of the anticipated capabilities of the chemical defense unit in nuclear emergency equipment reveals that the significance of command and support capabilities far surpasses that of the other four dimensions. The decontamination and recovery capacity, along with the alert and containment capability, falls into the secondary tier; however, the former holds greater importance than the latter. Both the radiation monitoring capacity and personnel protection capability occupy the third tier, with their relative importance considered to be roughly equivalent.

3.2.2 $U$ establishment of the factor set $U$

$U$ = {Command and Support Capability A1, Radiation Monitoring Capability A2, Alert and Containment Capability A3, Decontamination and Recovery Capability A4, Personnel Protection Capability A5};

$U_1$ = {Nuclear Emergency Command Capability A11, Nuclear Emergency Support Capability A12}

$U_2$ = {Nuclear Emergency Monitoring Capability A21, Nuclear Emergency Data Transmission Capability A22}

$U_3$= {Nuclear Emergency Suppression Capability A31, Nuclear Emergency Autonomous Operations Capability A32}

$U_4$ = {Decontamination Capability A41, Nuclear Emergency Recovery Capability A42}

$U_5$ = {Individual Emergency Response Protection Capability A51, Personnel Respiratory Support Capability A52, Monitoring Capability for Emergency Personnel's Vital Signs and Locational Tracking A53}

3.2.3 Determination of weights

$$W = \begin{pmatrix} w_1 & w_2 & w_3 & w_4 & w_5 \end{pmatrix} = \begin{pmatrix} 0.407 \\ 0.081 \\ 0.177 \\ 0.240 \\ 0.093 \end{pmatrix}^T \quad (15)$$

Where $W_1 = \begin{pmatrix} 0.75 & 0.25 \end{pmatrix}$, $W_2 = \begin{pmatrix} 0.5 & 0.5 \end{pmatrix}$, $W_3 = \begin{pmatrix} 0.666 & 0.333 \end{pmatrix}$, $W_4 = \begin{pmatrix} 0.8 & 0.2 \end{pmatrix}$

$W_5 = \begin{pmatrix} 0.539 & 0.297 & 0.163 \end{pmatrix}$

3.2.4 Establishment of the evaluation comment set

The evaluation comment set comprises five fuzzy levels, represented as: "Very Poor, Poor, Fair, Good, Excellent".

3.2.5 Determination of the membership degree matrix

The determination of the membership degree matrix is typically conducted by experts who utilize their practical experience, combined with real-world contexts, to score each item within the indicator system. They select the corresponding membership degree levels, after which the evaluations from multiple experts are statistically analyzed. Following normalization, the corresponding membership degrees are obtained, leading to the construction of the membership degree evaluation matrix.

A survey comprising a questionnaire was distributed to ten experts for the evaluation of the secondary indicators. Upon collecting the responses, the frequency of each indicator was recorded, resulting in the findings presented in Table 3.

**Table 3. Evaluation Results**

| Primary Indicator | Secondary Indicator | Excellent | Good | Fair | Poor | Very Poor |
|---|---|---|---|---|---|---|
| Command and Support Capability (A1) | Nuclear Emergency Command Capability (A11) | 7 | 2 | 1 | | |
| | Nuclear Emergency Support Capability (A12) | 6 | 3 | 1 | | |
| Radiation Monitoring Capability (A2) | Nuclear Emergency Monitoring Capability (A21) | 2 | 5 | 3 | | |
| | Nuclear Emergency Data Transmission Capability (A22) | 5 | 4 | 1 | | |
| Alert and Containment Capability (A3) | Nuclear Emergency Suppression Capability (A31) | 5 | 1 | 4 | | |
| | Autonomous Operations Capability (A32) | 6 | 3 | | 1 | |
| Decontamination and Recovery Capability (A4) | Decontamination Capability (A41) | | 4 | 5 | 1 | |
| | Recovery Capability (A42) | 1 | 4 | 4 | 1 | |
| Personnel Protection Capability (A5) | Individual Emergency Response Protection Capability (A51) | 5 | 4 | 1 | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Personnel Respiratory Support Capability (A52) | 4 | 2 | 3 | 1 | |
| | Monitoring Capability for Emergency Personnel's Vital Signs and Locational Tracking (A53) | 5 | 3 | 2 | | |

### 3.3 Evaluation Results

3.3.1 Primary fuzzy comprehensive evaluation

According to equation (15), the evaluation vector for Command and Support Capability, denoted as $B_1$, is derived as follows:

$$W_1=\begin{pmatrix}0.750 & 0.250\end{pmatrix}$$

$$R_1=\begin{pmatrix}0.7 & 0.2 & 0.1 & 0 & 0\\ 0.6 & 0.3 & 0.1 & 0 & 0\end{pmatrix}$$

$$B_1=W_1\circ R_1=\begin{pmatrix}0.675 & 0.225 & 0.100 & 0 & 0\end{pmatrix}$$

Similarly, the evaluation vector for Radiation Monitoring Capability, denoted as $B_2$, is obtained:

$$B_2=W_2\circ R_2=\begin{pmatrix}0.35 & 0.45 & 0.2 & 0 & 0\end{pmatrix}$$

The evaluation vector for Alert and Containment Capability, denoted as $B_3$, is determined as:

$$B_3=W_3\circ R_3=\begin{pmatrix}0.533 & 0.166 & 0.266 & 0.033 & 0\end{pmatrix}$$

The evaluation vector for Decontamination and Recovery Capability, denoted as $B_4$, is calculated as:

$$B_4=W_4\circ R_4=\begin{pmatrix}0.02 & 0.4 & 0.48 & 0.1 & 0\end{pmatrix}$$

The evaluation vector for Personnel Protection Capability, denoted as $B_5$, is defined as:

$$B_5=W_5\circ R_5=\begin{pmatrix}0.469 & 0.323 & 0.175 & 0.029 & 0\end{pmatrix}$$

3.3.2 Fuzzy comprehensive evaluation

$$W=\begin{pmatrix}0.407 & 0.081 & 0.177 & 0.240 & 0.093\end{pmatrix}$$

$$Q=\begin{pmatrix}0.675 & 0.225 & 0.1 & 0 & 0\\ 0.35 & 0.45 & 0.2 & 0 & 0\\ 0.533 & 0.166 & 0.266 & 0.033 & 0\\ 0.02 & 0.4 & 0.48 & 0.1 & 0\\ 0.469 & 0.323 & 0.175 & 0.029 & 0\end{pmatrix}$$

$$S=W\circ Q=\begin{pmatrix}0.445 & 0.283 & 0.235 & 0.032 & 0\end{pmatrix}$$

3.3.3 Calculation of Overall Score

Let $E$ represent the comprehensive score of the expected capabilities of a certain chemical defense unit's nuclear emergency equipment:

$$E=\begin{pmatrix}90 & 80 & 70 & 60 & 50\end{pmatrix}\cdot S^T=81.06$$

Command and Support Capability $E_1$:

$$E_1=\begin{pmatrix}90 & 80 & 70 & 60 & 50\end{pmatrix}\cdot B_1^T=85.75$$

Radiation Monitoring Capability $E_2$:

$$E_2=\begin{pmatrix}90 & 80 & 70 & 60 & 50\end{pmatrix}\cdot B_2^T=81.5$$

Alert and Containment Capability $E_3$:

$$E_3=\begin{pmatrix}90 & 80 & 70 & 60 & 50\end{pmatrix}\cdot B_3^T=81.85$$

Decontamination and Recovery Capability $E_4$:

$$E_4=\begin{pmatrix}90 & 80 & 70 & 60 & 50\end{pmatrix}\cdot B_4^T=73.4$$

Personnel Protection Capability $E_5$:

$$E_5=\begin{pmatrix}90 & 80 & 70 & 60 & 50\end{pmatrix}\cdot B_5^T=82.04$$

Based on the maximum degree of membership criterion and the given evaluations, the final score for the chemical defense unit is 81.06, indicating that its expected capabilities in nuclear emergency equipment are rated as "Good". This score serves as a microcosm of the current construction of nuclear emergency equipment, aligning well with its designation as a national-level emergency response force.

## 4. Conclusions

By employing the aforementioned evaluation model in conjunction with the current state of nuclear emergency tasks and equipment development within the military, a comprehensive assessment of the nuclear emergency rescue equipment system can be achieved. The insights gained can yield significant implications, such as identifying high-scoring indicators that warrant continued reinforcement, such as the procurement of decontamination vehicles and heavy radiation protection suits. Conversely, indicators with lower evaluation scores, such as joint operational communication equipment, must be prioritized for improvement. This approach not only provides robust guidance for the development of nuclear emergency equipment but also offers theoretical support for the effective execution of nuclear emergency rescue operations within the context of joint military tasks.

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