



A Weighted Scoring Model with One-Vote Veto Mechanism for Firefighting Capability Assessment of Dedicated Fire Brigades at Nuclear Power Plants

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Abstract. Conventional firefighting capability assessment methods predominantly rely on linear additive scoring, which is ill-suited to the radiological hazards, safety-system protection constraints, and the non-negotiable regulatory bottom lines that characterize dedicated fire brigades at nuclear power plants (NPPs). To address this gap, this paper proposes a quantitative assessment model integrating weighted scoring with a one-vote veto mechanism. The model employs a dual-track architecture: a deduction-based Category A compliance score (maximum 100 points) and a cumulative Category B incentive score (maximum 20 points), overlaid with a discrete veto layer to form a three-tier piecewise-based judgment structure of “compliance baseline — excellence incentive — veto cut-off.” The veto mechanism defines five non-compensable conditions: v_1 (failure to maintain 24-hour duty system), v_2 (annual comprehensive drill count below regulatory minimum), v_3 (emergency plan failing to define reactor safety shutdown boundaries), v_4 (triggering of any safety-critical deduction item), and v_5 (fire station location or response capability failing to meet regulatory requirements). Any single veto condition, when triggered, automatically downgrades the final grade to Unqualified regardless of aggregate scores. The model encompasses 4 first-level indicators, 26 third-level indicators (80 deduction items), and 5 Category B dimensions (48 scoring items). Indicator weights were determined through the Delphi method with a panel of 15 experts (comprising senior NPP fire protection engineers, nuclear safety regulators, fire brigade commanders, radiological protection specialists, and human factors experts), achieving a Kendall coefficient of concordance $W = 0.71$ ($p < 0.01$), indicating strong expert consensus. Field validation conducted over 5 days at a coastal four-unit PWR nuclear power plant in China yielded a Category A score of 84.8/100 (Grade: Qualified); weight analysis identified response time (relative weight 9.0%) as the highest-risk indicator. The current validation is limited to a single PWR plant; multi-plant validation covering a northern cold-region PWR, a BWR, and a small modular NPP is planned to establish the model’s generalizability across reactor types, climate conditions, and plant scales. The proposed model provides a standardized, quantifiable methodological framework for capability assessment of dedicated NPP fire brigades.

Keywords: nuclear power plant fire brigade, capability assessment, weighted scoring model, one-vote veto mechanism, Fire Hazard Analysis (FHA), dual-track scoring

1 Introduction

1.1 Research Background

Fire scenarios in NPPs differ fundamentally from those in conventional industrial facilities: cable fires in confined spaces, transformer oil fires adjacent to safety systems, hydrogen-cooled generator fires, and the critical constraint that firefighting actions must not compromise reactor safety systems ^[1,2,5]. The 2011 Fukushima Daiichi accident demonstrated that NPP fires can trigger cascading failures—the destruction of firefighting infrastructure led directly to loss of fire suppression capability, exacerbating the accident consequences ^[3]. In the aftermath, regulatory bodies worldwide intensified scrutiny of NPP fire brigade readiness. For example, China's National Energy Administration issued the first dedicated regulation on NPP fire station construction in 2024 ^[19], establishing minimum staffing, vehicle, and facility requirements. These developments reflect the demand for standardized and scientifically grounded assessment methods ^[21].

The IAEA Safety Guide NS-G-1.7 ^[5] and NS-G-2.1 ^[1] respectively establish the defense-in-depth principle for NPP fire safety and the organization, equipment, and training requirements for fire brigades, while the U.S. NRC Regulatory Guide 1.189 ^[2] provides detailed fire protection guidance for operating reactors. However, these guides focus on system design requirements and qualitative principles, lacking a quantitative assessment model for comprehensive fire brigade capability.

1.2 Research Gaps

Fire department capability assessment has been extensively studied in municipal and industrial contexts, but the NPP domain presents research gaps at three levels:

1. Model level: Additive compensation and the absence of nonlinear judgment. Existing fire assessment models (e.g., NFPA 1710 ^[4], AHP-fuzzy comprehensive evaluation methods ^[8]) all employ linear additive scoring mechanisms, where outstanding performance in one dimension can mask critical deficiencies in another ^[6,7]. A fire brigade that is physically fit but unfamiliar with radiological zone entry procedures could pass the rating based on the aggregate score alone, while a nuclear-safety-critical capability gap remains concealed. The nuclear safety domain operates under a "bottom-line must not be breached" regulatory logic—certain serious individual deficiencies (such as failure to maintain a 24-hour duty system) should trigger an automatic veto rather than be compensated by high scores elsewhere. Conventional linear models cannot handle such nonlinear judgment requirements.

2. Guidance level: Disconnect between qualitative requirements and quantitative methods. Nuclear safety guides (IAEA NS-G-1.7 ^[5], NS-G-2.1 ^[1]) provide qualitative

requirements for fire brigade development but offer no quantitative assessment methodology. NPP fire protection involves inherently overlapping assessment dimensions—tactical coordination quality affects response time, and communication failures simultaneously involve equipment integrity and command capability^[8,9,20]—and the absence of formal non-duplicate deduction rules inevitably leads to scoring disputes.

3. Object level: The lack of team capability profiling. Human reliability analysis (HRA) models (SPAR-H, CREAM^[10]) focus on the cognitive error probability of main control room operators rather than the multi-dimensional capability profiling of emergency response teams. Recent research on the resilience of NPP emergency response organizations^[22] has begun applying quantitative methods such as Delphi-AHP to identify influencing factors, but an integrated assessment framework encompassing fire, radiation, and organizational dimensions remains absent.

1.3 Contributions

The main contributions of this paper are as follows:

1. Introducing the Fire Hazard Analysis (FHA) as a cross-cutting assessment benchmark for NPP dedicated fire brigade capability evaluation for the first time, establishing an FHA-driven assessment loop across five dimensions: emergency plan development, drill scenario coverage, vehicle configuration, training content, and response testing.

2. Constructing a three-tier piecewise-based comprehensive scoring model that combines dual-track scoring (deduction + accumulation) with a one-vote veto mechanism, structurally separating the three logical layers of compliance baseline assessment, excellence incentive evaluation, and veto cutoff, overcoming the score compensation problem inherent in purely additive models.

3. Completing field application validation at a coastal four-unit NPP in China, demonstrating the diagnostic effectiveness and engineering applicability of the model.

2 Assessment System Design

2.1 Indicator Selection Principles and System Architecture

The indicator selection for this assessment system follows the SMART principle (Specific, Measurable, Achievable, Relevant, Time-bound) and, building upon the specific characteristics of NPP fire protection, establishes three nuclear-safety-specific screening criteria:

Criterion 1 (FHA-driven): Any fire-related indicator must be evaluated against the plant-specific FHA conclusions as the benchmark.

Criterion 2 (Nuclear safety priority, implementing the Nuclear Safety Culture Policy Statement^[13]): Indicators involving nuclear safety system protection and radiological zone entry authorization receive priority in weight allocation and deduction values.

Criterion 3 (Radiological protection synergy, per GB 18871^[12]): Operations entering radiological controlled areas must have corresponding radiological protection knowledge, equipment, and procedural indicators evaluated in tandem.

Table 1. Summary of Category A indicator system structure and maximum scores.

First-level Indicator	Second-level Indicator	Third-level Indicator	Max Score	
1. Brigade Comprehensive Capability (28)	1.1 Staffing and Qualifications	1.1.1 Duty personnel allocation	3	
		1.1.2 Personnel basic requirements	2	
	1.2 Professional Competence	1.2.1 Theoretical knowledge	5	
		1.2.2 Physical fitness	4	
		1.2.3 Individual operational skills	3	
		1.2.4 Team tactical coordination	4	
		1.2.5 Plant familiarity	2	
	1.3 Daily Management	1.3.1 Institutional development and implementation	3	
		1.3.2 Assessment management	2	
		1.3.1 Station location and garage	1	
2. Equipment, Facilities and Support (27)	2.1 Station and Facilities	2.1.2 Communication and support systems	2	
		2.2.1 Vehicle configuration	7	
	2.2 Vehicles and Equipment	2.2.2 Conventional equipment configuration	8	
		2.3.1 Material support	3	
	2.3 Material Support and Maintenance	2.3.2 Equipment maintenance and inspection	2	
		2.4.1 Fixed system familiarity and coordination	4	
	2.4 Fixed Fire Protection System Integration	3.1.1 Training system and hours	2	
		3.1.2 Training content	7	
	3. Training and Emergency Preparedness (24)	3.2 Plans and Drills	3.2.1 Emergency plan development and management	5
			3.2.2 Drill execution	7
3.2.3 Post-drill review and summary			3	
4.1 Duty and Response		4.1.1 Duty system	2	
		4.1.2 Response timeliness	9	
4.2 Coordinated Operations		4.1.3 Fire communication and command capability	2	
	4.2.1 Internal coordinated operations	5		
	4.2.2 External joint response	3		
Category A Total			100	

Based on the above principles, a three-level assessment indicator system was constructed. The system incorporates internationally recognized firefighter qualification standards (NFPA 1001^[11]) and occupational health requirements (NFPA 1582^[17]) as normative references for personnel-related indicators. The resulting indicator system structure is shown in Table 1.

The Category B excellence incentive system comprises 5 indicators, each capped at 4 points (total 20 points), as shown in Table 2.

Table 2. Category B indicator system structure.

Category B Indicator	Focus Area	Cap	Representative Scoring Items
B.1 Position Authorization and Incentives	Formal authorization procedures, compensation and benefits, psychological support, elite development programs	4	11 items covering authorization procedures, OJT integration, compensation assessment, non-material incentives, satisfaction surveys, etc.
B.2 Personnel Professional Qualifications	Certification coverage, hierarchical advancement, international certification, certification-driven training	4	9 items covering national vocational qualification rates, intermediate/advanced certificates, certified fire protection engineers, international certifications, etc.
B.3 Training Facilities and Methods	Advanced training infrastructure, VR/simulation systems, digital management platforms, innovative training technologies	4	9 items covering smoke/heat training chambers, VR simulators, digital platforms, scenario-specific simulation facilities, AI-assisted training, etc.
B.4 Equipment Technological Advancement	UAV systems, firefighting robots, personnel positioning and communication, radiation-specific detection, systematic equipment renewal	4	10 items covering reconnaissance UAVs, firefighting robots, indoor positioning, mobile command, gamma cameras, etc.
B.5 Position-Differentiated Training	Position classification, independent training programs, position certification, SAT design, capability visualization	4	9 items covering ≥ 5 position categories, independent syllabi, certification procedures, JTA documentation, capability radar charts, etc.
Category B Total		20	48 scoring items

Category B indicators are not mandatory; small NPPs or newly commissioned plants may not meet the scoring conditions for B.3 and B.4 items, which does not affect the overall grade determination.

2.2 Dual-Track Scoring Mechanism Design Logic

This assessment system adopts a dual-track design of "bottom-line constraint + positive incentive". The dual-track design is necessary because the nuclear safety domain requires that certain fundamental deficiencies—failure to maintain 24-hour duty, omission of reactor safety boundaries in emergency plans—be treated as non-compensable: no aggregate score, however high, can offset them. A single additive scoring track would mathematically allow such critical gaps to be masked by high performance in unrelated dimensions, which is unacceptable in NPP fire brigade assessment.

Category A Deduction System (100 points): Each third-level indicator starts from its maximum score and is deducted item by item according to the deduction criteria until exhausted. The Category A score constitutes the hard threshold for grade determination—regardless of how high the Category B score is, a brigade whose Category A score does not reach the corresponding grade threshold shall not enter that grade.

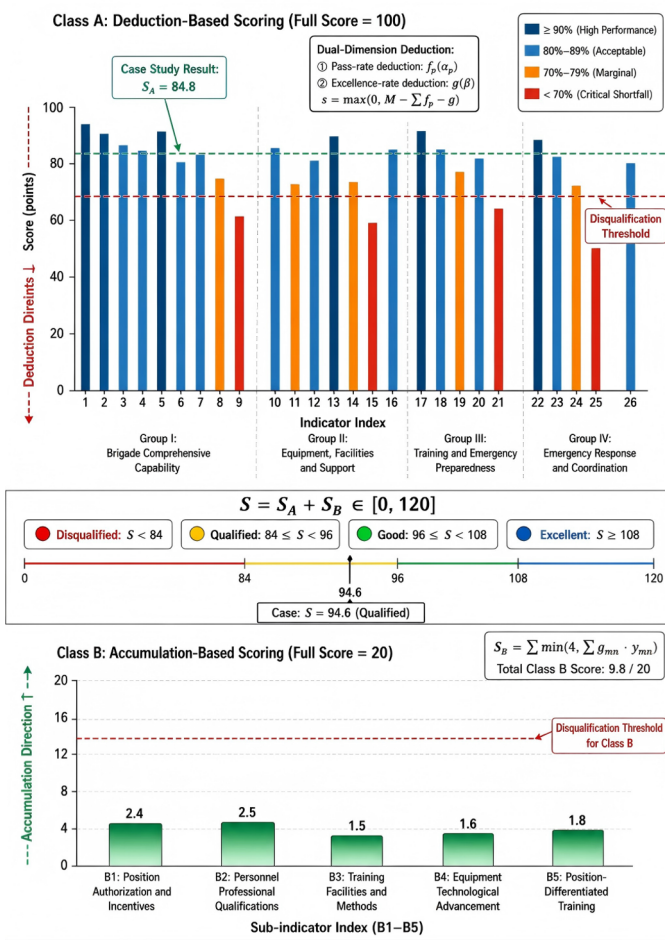


Fig. 1. Schematic diagram of the dual-track scoring mechanism.

Category B Cumulative Scoring System (20 points): Each scoring item is independently assessed; points are awarded upon meeting the criterion, with each indicator capped at 4 points. The Category B score reflects only the degree of advancement and does not require full achievement of all items.

This dual-track system achieves structural separation of "compliance" and "excellence" in assessment logic. Figure 1 illustrates the dual-track scoring mechanism.

2.3 FHA-Driven Cross-Cutting Design

The Fire Hazard Analysis (FHA) is the core document for NPP fire protection design, identifying critical fire protection zones, fire scenarios, safety system protection requirements, and fire protection measure configurations for the plant [1]. This paper introduces FHA as a cross-cutting assessment benchmark for the first time:

1. Emergency plan development (3.2.1): Requires development of specific response plans for each major fire scenario identified in the FHA, in accordance with emergency planning criteria ^[16]; plan content must adopt FHA fire scenario parameters and implement FHA-specified fire protection measures; plans must be synchronously revised upon FHA updates.

2. Drill scenario coverage (3.2.2): Requires drill scenarios to cover all critical safety areas identified in the FHA (nuclear island, turbine building, cable galleries, diesel generator rooms, etc.).

3. Vehicle configuration (2.2.1): Requires fire vehicle configuration to align with major fire scenarios identified in the plant-specific FHA. Elevated platform vehicle provision includes an FHA precondition—triggered only when the FHA identifies high-rise fire scenarios requiring elevated platform vehicle intervention.

4. Training content (3.1.2): Requires nuclear firefighting tactical training content to be designed in conjunction with critical fire scenarios identified in the plant-specific FHA.

5. Response testing (4.1.2): Unannounced test fire points are uniformly selected as the most distant critical fire protection area from the fire station among those identified in the FHA.

This design transforms the assessment from a "generic fire protection capability inspection" into a "targeted capability diagnosis aligned with the plant's actual risk profile," making this assessment system distinct from generic fire brigade evaluations.

3 Quantitative Assessment Model

3.1 Multi-Level Weighted Scoring Model

Model Structure Definition.

Let the assessment system be a three-level hierarchical structure: first-level indicators $I_i (i = 1, 2, 3, 4)$, second-level indicators I_{ij} , and third-level indicators I_{ijk} .

The Category A composite score is defined as the sum of the actual scores of all third-level indicators:

$$S_A = \sum_{i=1}^4 \sum_j \sum_k S_{ijk} \quad (1)$$

where S_{ijk} is the actual score of the (k)-th third-level indicator under the (j)-th second-level and (i)-th first-level indicator, satisfying the deduction constraint:

$$s_{ijk} = \max(0, M_{ijk} - \sum_l d_{ijkl} \cdot x_{ijkl}) \quad (2)$$

Where M_{ijk} is the maximum score of the third-level indicator, d_{ijkl} is the deduction value of the (l)-th deduction item ($d_{ijkl} > 0$), $x_{ijkl} \in \{0, 1, \mathbb{Z}^+\}$ is a binary/count trigger variable (0 = not triggered, 1 = triggered once, positive integer = multiple triggers).

The Category B cumulative score is defined as:

$$S_B = \min\left(20, \sum_{m=1}^5 \min(4, \sum_n g_{mn} \cdot y_{mn})\right) \quad (3)$$

where g_{mn} is the score value of the (n)-th scoring item of the (m)-th Category B indicator, and $y_{mn} \in \{0,1\}$ is a binary satisfaction state variable. The total score:

$$S = S_A + S_B, \quad S \in [0,120] \quad (4)$$

Indicator Weight Normalization.

To facilitate cross-indicator comparison, a normalized score rate R_{ijk} is introduced:

$$R_{ijk} = \frac{s_{ijk}}{M_{ijk}} \times 100\% \quad (5)$$

First-level indicator score rate:

$$R_i = \frac{\sum_j \sum_k s_{ijk}}{\sum_j \sum_k M_{ijk}} \times 100\% \quad (6)$$

Weight Determination Method.

In this model, the weight of each indicator is embedded in its maximum score M_{ijk} (Category A) and individual scoring cap (Category B). The sum of all Category A maximum scores is normalized to 100 points, and the sum of Category B caps is normalized to 20 points:

$$w_{ijk} = \frac{M_{ijk}}{100}, \quad \sum_{i,j,k} w_{ijk} = 1 \quad (7)$$

$$w_m^B = \frac{C_m}{20} \sum_{m=1}^5 w_m^B = 1 \quad (8)$$

where $C_m = 4$, equally allocated across all 5 Category B indicators.

Weights were determined through the Delphi method. A panel of 15 experts (comprising 5 senior NPP fire protection engineers, 3 nuclear safety regulators, 3 fire brigade commanders with NPP service experience, 2 radiological protection specialists, and 2 human factors engineering and training system design experts) conducted two rounds of independent scoring and consensus building, assigning maximum scores (i.e., weights) to each indicator under the aggregate constraints of 100 points for Category A and 20 points for Category B. After two rounds, the Kendall coefficient of concordance (W) reached 0.71 ($(p < 0.01)$), and the median of each indicator was adopted as the final maximum score.

Weight allocation principles. The final weight distribution (Table 3) reflects the following priorities:

- Fixed systems first. Indicator 2.4.1 (Fixed system familiarity and coordination, 4 points) has the highest weight among knowledge/skill indicators, as fixed fire suppression systems constitute the first line of defense for NPP fire safety.
- Team over individual. Indicator 1.2.4 (Team tactical coordination, 4 points) is weighted higher than 1.2.3 (Individual operational skills, 3 points), reflecting the team-based nature of NPP firefighting.

- Performance over input. Response performance indicators (4.1.2, 9 points) are weighted substantially higher than training input indicators (3.1.1, 2 points), prioritizing actual operational performance over documentation.
- Duty as foundation. The 24-hour duty system (4.1.1, 2 points) is elevated from the general procedural weight tier, as it constitutes the prerequisite for all response capabilities.
- To evaluate the impact of weight allocation on the final rating, a $\pm 1\%$ perturbation analysis was conducted on the indicator with the highest relative weight, 4.1.2 (response timeliness, 9.0%). When the weight was adjusted from 9.0% to 8.0% and 10.0% (with other indicators proportionally scaled to maintain the aggregate constraint), the Category A score of NPP-A changed by less than 1.5 points, and the grade determination (Qualified) remained unchanged, indicating reasonable robustness of the model to minor weight perturbations. A more comprehensive weight sensitivity analysis awaits the accumulation of multi-plant data.

Table 3. Weight distribution and allocation rationale (selected key indicators).

Indicator	Max Score (M_{ijk})	Relative Weight (%)	Allocation Rationale
1.2.1 Theoretical knowledge	5	5.0	Multi-dimensional knowledge: fire theory + nuclear safety + FHA + coordination + tactics
1.2.2 Physical fitness	4	4.0	Percentage trigger mechanism; individual fitness as a team-level concern
1.2.4 Team tactical coordination	4	4.0	Team operations are central to NPP firefighting; weight higher than individual skills
2.4.1 Fixed system familiarity and coordination	4	4.0	Fixed systems are the first line of defense; a nuclear-safety-specific indicator
3.2.1 Emergency plan development and management	5	5.0	FHA-driven scenario coverage is a distinguishing feature of this system
3.2.2 Drill execution	7	7.0	Drill quality directly reflects operational readiness
4.1.1 Duty system	2	2.0	24-hour duty is the prerequisite for all response capabilities; elevated above conventional procedural weight
4.1.2 Response timeliness	9	9.0	Highest single-indicator weight; the ultimate test of fire brigade effectiveness
4.2.1 Internal coordinated operations	5	5.0	Cross-departmental coordination (operations + radiological protection) is a NPP-specific requirement

3.2 One-Vote Veto Nonlinear Judgment Mechanism

Veto Condition Definition.

Five veto conditions $\mathcal{V} = \{v_1, v_2, v_3, v_4, v_5\}$ are established:

$$v_1 = 1[\text{No 24 - hour round - the - clock duty is in place}]$$

$v_2 = 1$ [The emergency plan lacks clear boundaries against actions impairing safety systems]

$$v_3 = 1 \left[\sum_{j \in \mathcal{J}_{\text{eit}}} 1_{ij} \geq 2 \text{ Within the same drill/spot check} \right]$$

$v_4 = 1$ [The fire station layout cannot ensure arrival within five minutes
 $\wedge$ 4.1.2 Full score deduction for any node]

$v_5 = 1$ [No comprehensive drills have been conducted in the past year]

where $1[\cdot]$ is the indicator function, and $\mathcal{J}_{\text{eit}}$ in v_3 is the set of safety-critical deduction items. Veto condition trigger:

$$V = V_{q=1}^5 v_q \quad (9)$$

The verification of veto conditions is executed independently of the A/B scoring process: (v_1) (duty system) and (v_5) (annual drill count) are confirmed by the assessment team leader through document review prior to assessment commencement; (v_2) (plan safety boundaries) and (v_3) (safety-critical deduction items) are flagged during the scoring process; and (v_4) (fire station location and response) is verified after response testing. This procedure ensures that veto determinations are not subject to subjective interference during the scoring process.

Piecewise Grade Determination Function.

The final grade determination function is:

$$\text{Grade} = \begin{cases} \text{Unqualified} & V = 1 \\ \text{Excellent} & V = 0 \wedge S_A \geq 90 \wedge S \geq 108 \\ \text{Good} & V = 0 \wedge S_A \geq 80 \wedge S \geq 96 \\ \text{Qualified} & V = 0 \wedge S_A \geq 70 \wedge S \geq 84 \\ \text{Unqualified} & V = 0 \wedge S_A < 70 \end{cases} \quad (10)$$

In the above grade determination, the Category A score thresholds (70/80/90) constitute insurmountable hard thresholds—regardless of how high the Category B score is, a brigade whose Category A score does not meet the threshold cannot enter the corresponding grade. However, provided that the Category A threshold is met, the Category B score can assist the brigade in reaching a higher total score (S) threshold (e.g., Good requires $S \geq 84$), thereby playing a limited auxiliary promotion role between adjacent grades. This design ensures that the compliance baseline is not compensated by excellence performance, while leaving room for positive incentives for comprehensive development.

This mechanism mathematically superposes a discrete veto layer $V \in \{0,1\}$ onto a continuous linear scoring space $S \in \{0,120\}$, such that the scoring outcome space degenerates from a continuous interval into a segmented structure of {Unqualified, Qualified, Good, Excellent} (under the premise of Category A compliance). This structure captures the "bottom-line must not be breached" regulatory logic of the nuclear safety domain.

4 Case Validation

4.1 Assessment Subject and Process

The assessment was conducted at a nuclear power plant on the southeastern coast of China (designated "NPP-A"). The plant has four operating PWR units (2×990 MWe + 2×1080 MWe), with a dedicated fire brigade of 38 personnel organized into 4 duty shifts across 2 fire stations. The assessment spanned 5 days and included, in sequence: document review, an unannounced response test (simulated cable gallery fire at the most distant point), theoretical and equipment operation spot-checks (22 personnel for theory / 12 for physical fitness), a comprehensive drill observation (transformer oil fire with radiological release scenario, with joint participation of the operations shift, radiological protection section, and plant emergency organization), and structured interviews (12 interviewees, including firefighters, shift supervisors, a radiological protection engineer, and a local fire department liaison).

4.2 Assessment Results

The assessment results are shown in Table 4. Category A score: 84.8 points (score rate 84.8%). The deduction points for all specific penalty items are shown in Table 5. Category B score: 9.8 points (score rate 49.0%), with major contributions from Position Authorization and Incentives (2.4 points) and Personnel Professional Qualifications (2.5 points); scores were lower for Training Facilities (1.5 points, no VR/simulator systems) and Equipment Technological Advancement (1.6 points, no firefighting robots).

Veto condition check: ($V = 0$), none of the five veto conditions were triggered.

Final determination: ($S_A = 84.8$) (≥ 80), ($S = 84.8 + 9.8 = 94.6$) (≥ 84), Grade = Qualified

Table 4. NPP-A Category A assessment score summary.

First-level Indicator	Max Score	Actual Score	Score Rate (%)
1. Brigade Comprehensive Capability	28	23.2	82.9
2. Equipment, Facilities and Support	27	24.5	90.7
3. Training and Emergency Preparedness	24	19.8	82.5
4. Emergency Response and Coordination	21	17.3	82.4
Category A Total	100	84.8	84.8

5 Discussion and Conclusion

5.1 Discussion

This model is applicable to PWR, BWR, or PHWR nuclear power plants that use FHA as the basis for fire protection planning. Conditional clauses for cold climate operations (triggered when the annual minimum temperature $\leq -15^\circ\text{C}$) and elevated platform vehicles (triggered by FHA-identified high-rise fire scenarios) ensure that the model does not penalize assessed subjects for requirements irrelevant to the plant's actual conditions. The limitations of the model are primarily threefold: (1) some deduction items

rely on the assessor's subjective judgment, which can be addressed in the future by establishing quantified anchoring standards through the Behaviorally Anchored Rating Scale (BARS) approach; (2) the weights were determined through the Delphi method, and although strong consensus was achieved ($W = 0.71$), they still reflect the composition and experience of the expert panel convened—future research may employ the entropy weight method to derive objective weights from multi-plant assessment data for quantitative comparison; (3) the current case study is based on a single NPP, and the generalizability of the model awaits multi-plant validation.

Table 5. NPP-A Category A deduction values summary

Deduction Items	Deduction Values	Deduction Items	Deduction Values
Over 10% of one team member's personnel file entries missing	0.2	Incomplete inbound and outbound inventory records	0.4
The average overall score of randomly inspected team members is below 80 points	1	No operation manual for fixed fire-fighting facilities compiled by the fire team	0.4
Missing annual physical fitness assessment records	0.5	Annual on-the-job training hours fail to meet required standards	0.5
One instance of excessive SCBA donning time by personnel	0.5	Training curriculum excludes response drills for non-radioactive hazardous chemical incidents	0.5
One instance of non-standard hose laying and rewinding operation by personnel	0.5	Training manuals have not been updated for over three years	0.5
One instance of non-standard radio communication terminology used by the team	0.4	Post-fire restoration and re-entry procedures are absent from emergency preplans	0.5
Failure to maintain adequate safety distance	0.4	Insufficient frequency of tabletop exercises	1.2
Insufficient recorded times for the "Six Familiarization" exercise	0.3	After-action review reports are compiled in a perfunctory manner lacking substance	1
Mental health management system not established	0.3	One instance of post abandonment during night shift	0.3
Formalistic implementation of management rules	0.5	Delayed emergency response	1.5
One newly recruited staff participated in duty prior to completing pre-job assessment	0.2	No written fire communication regulations formulated	0.5
No periodic test records for communication equipment	0.2	Unauthorized removal of protective equipment	0.3
One discrepancy found between vehicle ledger and actual vehicle	0.5	Poor communication between fire crew and main control room	0.4
Improper storage conditions for chemical protective clothing against specifications	0.5	Failure to submit nuclear safety risk notification to local fire rescue authority	0.4
One SCBA cylinder overdue for hydrostatic pressure test	0.5	Failure to hand over basic plant fire protection documents to local fire rescue authority	0.3

To address the subjective judgment concern, the NPP-A field assessment employed a three-assessor panel with independent, parallel scoring of all 80 Category A deduction items. The initial inter-rater agreement rate—defined as the proportion of deduction items where all three assessors independently reached identical trigger/non-trigger determinations—exceeded 85%, with discrepancies resolved through facilitated consensus discussion referencing the written deduction criteria and the FHA documentation. This process demonstrates that the deduction criteria provide a sufficiently objective basis for consistent application across assessors.

Regarding model deployment, the current validation is limited to NPP-A (PWR) only. Future multi-plant comparative validation is planned for the following NPP types: (1) a northern cold-region PWR NPP, to test the triggering and assessment effect of cold climate clauses; (2) a BWR NPP, to verify the applicability of the FHA-driven design across different reactor types; (3) a single-unit or dual-unit small NPP, to test the effectiveness of the Category B indicator exemption mechanism. Multi-plant validation will cover different reactor types, climate conditions, and unit scales, requiring assessment data from no fewer than 3 NPPs to support generalizability conclusions.

Regarding assessment efficiency, the full assessment of 128 scoring items (5 days) is suitable for the 5-year cyclical in-depth assessment cycle. For annual routine inspections, it is recommended to extract approximately 20 core indicators (including the 5 high-weight indicators such as 4.1.2 Response Timeliness, 3.2.2 Drill Execution, and 2.2.1 Vehicle Configuration, together with veto conditions v_1-v_5), forming a streamlined 1–2 day version to reduce assessment costs and increase annual execution rates.

In terms of international benchmarks, the U.S. NEI 07-05 provides a qualitative framework for NPP fire brigade drill assessment, while the French EDF has established a scenario-simulation-centered fire brigade certification system. The present model differs from these frameworks primarily in its adoption of FHA as a cross-cutting quantitative assessment benchmark and the introduction of a non-compensable veto mechanism to enforce nuclear safety bottom-line requirements.

Future research may advance along three directions: (1) constructing a Bayesian network model, training conditional probability tables with assessment data to predict possible score intervals for other indicators given partial indicator scores and to identify the root cause nodes with the greatest impact on overall capability; (2) converting assessment scores into fire brigade response success probability modification factors via mapping functions, embedding them into PSA fire event trees [14,15,18] to quantify the contribution of fire brigade capability levels to plant Core Damage Frequency (CDF); (3) on the basis of accumulated multi-plant, multi-year assessment data, training machine learning models such as Random Forest or XGBoost to predict score trends for each indicator in subsequent assessments, enabling a shift from retrospective evaluation to forward-looking early warning.

5.2 Conclusion

This paper applied the proposed weighted scoring and one-vote veto assessment model to a field validation at a coastal four-unit PWR nuclear power plant in China. The results demonstrate that: (1) the Category A compliance score was 84.8/100 (Grade: Qualified),

and the model effectively identified three primary weakness dimensions—generally low theoretical knowledge levels, insufficient tabletop exercise frequency, and missing fixed system operating manuals; (2) the dual-track scoring and one-vote veto mechanism structurally separated compliance judgment from excellence incentives, avoiding the compensation effect of high-scoring indicators on safety deficiencies inherent in traditional additive scoring; (3) weight analysis identified response timeliness (relative weight 9.0%) as the highest-risk indicator affecting comprehensive capability, and it is recommended that plants prioritize this dimension in training plans and equipment configuration. However, the present validation is based on a single PWR nuclear power plant (NPP-A), which constitutes the primary limitation of this study. The generalizability of the proposed model across different reactor types (BWR, PHWR), climate conditions (northern cold-region plants), and plant scales (small modular NPPs with reduced staffing) remains to be established. A systematic multi-plant validation program is planned, encompassing at least three additional NPPs of distinct types and configurations, with comparative analysis of assessment outcomes to quantify model robustness and identify type-specific calibration needs. The FHA-driven design ensures that assessment results directly reflect the plant's actual fire risk profile, overcoming the disconnect between generic assessment standards and NPP-specific scenarios. The proposed model provides a quantifiable and comparable methodological framework for capability assessment of dedicated NPP fire brigades, and future multi-plant validation together with the coupling of assessment results to probabilistic safety analysis represents a key direction for enhancing its engineering applicability.

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