Integration of Nuclear Safety and Security in Research Reactors using a Monte Carlo Simulation aided Analytical Hierarchy Process

Keywords: nuclear security, nuclear safety, integration, analytical hierarchy process, research reactors

Abstract

All operations involving nuclear and radioactive materials require exercising principles of nuclear safety and security. The goal of both these disciplines is protection—protecting the public, the workers, and the environment from hazards associated with radiation exposure. Despite these disciplines having the same goal, they use different perspectives and methods to accomplish their respective goal. The difference in methods and perspectives has led the disciplines to work in parallel rather than together. Studies have found that operating these two disciplines separately is less effective than together, and these disciplines should be integrated to improve protection practices. This study analyzed the importance of integration in a research reactor across eight criteria where nuclear safety and security could work together. A survey tool was provided to research reactor staff and asked them to rate the eight criteria based on the analytical hierarchy process (AHP) methodology. The AHP is a multi-tiered method that uses a pairwise comparison matrix to rate criteria within and across each tier. A Monte Carlo simulation (using a beta-Program Evaluation Review Technique distribution) was applied to the AHP data to determine the criteria with the most importance for nuclear safety and security integration. Access control and transportation of nuclear material were rated as having the most importance for integration, indicating where nuclear safety and security integration would provide the most synergistic benefit in a research reactor and associated facilities.

1. Introduction

In 1968, the SL-1 reactor experienced an incident unrivaled by any other safety accident in the United States (US) history of radiation protection. Through a combination of events, the reactor underwent an uncontrolled criticality event that caused the destruction of the reactor core and the death of three workers. The event was unprecedented and unexpected (as many emergency situations are). Rapid response teams attempted to rescue the workers but quickly realized radiation levels were too high. Strategic interventions based on radiation protection principles were used to recover two of the deceased workers; however, a special team (assembled by the US Army) was required to recover the third individual (who was pinned to the ceiling). It took two years of nuclear forensic research and study to ascertain what had caused the accident. In the end, it was determined a lack of training among the three-man staff, and a failure of safety protocols from the previous shift, resulted in a catastrophe of events that elapsed in two seconds.[1]

The SL-1 reactor was a newly designed experimental reactor based on the BORAX design from Argonne National Laboratories (ANL). It was commissioned by the US Army to power remote operations to eliminate the need for regular diesel fuel shipments.[1] Today, research is being conducted on Small Modular Reactors (SMR) and Very Small Modular Reactors (VSMR) to understand their potential to power remote operations. The potential benefits of using these reactors include a power source that will not require fuel transportation (like carbon-powered sources) and relatively lower greenhouse emissions—things the US military is still very interested in.[2] The new SMR does not have the same design as the SL-1 and has improved safety features from years of development. However, the smaller footprint of an SMR (compared to the standard nuclear power plant) brings unique challenges. One of those challenges is security.

When interviewed by investigators during the aftermath of the SL-1 accident, investigators questioned technicians if they knew about the potential ease of creating an unintentional criticality event. The technicians responded in the affirmative. In fact, remembering this was during the Cold War era, the technicians stated that their plan for the reactor, if the USSR soldiers invaded and were going to overrun the facility, was to intentionally create a criticality event and sabotage the plant.[1] Given this perspective, we are provided with a unique perspective regarding the potential consequences of a successful sabotage event.

Much of nuclear safety has evolved in response to different historical accidents and safety events. Learning from these has increased our capabilities of operating safely in a nuclear environment. Conversely, nuclear security has not benefited from a similar history. Thankfully, we have not had many security events to evolve this protection discipline; however, we should not wait for a security event before considering methods to improve this discipline. One of the ways we can help improve security is to identify areas of integration between nuclear safety and security. Integration areas are found when the disciplines of nuclear safety and security agree on a practice or course of action. Identifying and applying these areas to a radiation protection program will promote synergy, yielding greater radiation protection than if safety and security are operated in parallel.

2. Methodology

To determine how integration can benefit the radiation protection program of a facility, we must first understand what integration is. The International Atomic Energy Agency (IAEA) describes the nuclear safety and security interface as the point where "safety and security complement one another" and where "the objectives of one do not compromise the objectives of the other."[3] The IAEA also discusses different points of integration between nuclear safety and security, such as defense-in-depth practices or the transport of nuclear materials. For the purposes of this research, eight integration points have been identified. These eight points have demonstrated the complements between nuclear safety and security and the potential to achieve synergy when these disciplines operate in an integrated manner.

2.1 Eight Points of Integration

Synergy is observed when two combined components produce a result greater than their individual sum—this is the goal of integration. The nuclear safety and security disciplines must be integrated to achieve synergy in a radiation protection program. This research identifies eight points of interdisciplinary integration, which in turn identifies where synergy can be found. The eight points in this study are access control, transportation of nuclear materials, transparency in emergency response, testing and maintenance, proper disposal of materials, training and education, defense in depth, and culture.

Access Control: Access control is the selective restriction of access to a place or resources. The IAEA's report, The Interface Between Safety and Security at Nuclear Power Plants (INSAG-24), best emphasizes the integration of nuclear safety and security in access control. It is noted in this report that access controls are considered vital as a safety function because these prevent (or limit) individuals from being exposed to dangerous situations.[4] The synergy is observed as access control also prohibits unauthorized access of malicious actors to vital areas (a focus of nuclear security).

Transport of Nuclear Materials: The transport of nuclear materials focuses on the measures taken to protect these materials from accidents, deliberate incidents, or other violations while in transit from origin to destination. The synergy of safety and security in material transportation is found in the transportation vessel design, route, and strategy. The ALARA safety principles of time, distance, and shielding are utilized throughout this process, complementing the objectives of nuclear security.[5]

Transparency in Emergency Response: The goals of response in a nuclear emergency include saving lives, controlling the situation, and mitigating consequences. Nuclear security objectives often focus on preventing and delaying access; however, this can be counteractive to emergency response. Only through transparency, coordination, and integration can the potential conflicts be mitigated, providing an emergency response plan with the ability to effectively accomplish its goals.[6]

Testing and Maintenance: Testing and maintenance include any form of routine, preventive, or corrective maintenance activities that are required to (1) assess the current condition and/or rate of degradation of equipment, (2) test the operation/functionality of equipment, or (3) prevent equipment failure that would eventually lead to safety or security concerns in the facility.[7] While the safety aspect of this criterion has been observed in a plethora of historical events (e.g., Three Mile Island, Chornobyl, and Tokaimura), the synergy of security has been implicated in specific attacks that have thwarted safety features (e.g., Stuxnet).

Proper Disposal of Materials: Responsible and proper disposal of radioactive materials includes spent fuel, nuclear waste, abandoned sources, orphan sources, and other radioactive waste resulting from civilian applications in industries such as oil and gas, construction, research, and medicine. Nuclear waste is often mixed and presents a complexity of risk. The measures taken to prevent accidental exposure to the waste material are akin to those designed to prevent the unauthorized access of malicious actors.[8]

Training and Education: A challenge often observed in the application of nuclear safety and security integration is the personnel practicing these two disciplines. Specifically, the personnel most often working in the safety discipline are the facility’s nuclear operators and radiation workers. However, the personnel most often working in the security discipline are the security personnel and response forces. Because these personnel operate independently, a gap is created, and they do not work together. The gap can be addressed through integrated training and education of the personnel that work in these parallel disciplines.[4]

Defense in depth: Defense in depth is an approach to security where a series of defensive mechanisms are layered to protect vital assets. If one security mechanism fails, another mechanism is activated to thwart the attack. Through this multi-layered concept, most threats to safety and security can be addressed and mitigated.[4]

Culture: Organizational culture consists of shared values, beliefs, expectations, and practices established by leaders and communicated through various methods, ultimately shaping employee perceptions, behaviors, and understanding.[9] It has been observed that safety culture within a facility has a direct impact on security culture—if safety culture is poor, then security culture will most likely be poor, too (and vice versa).[10] The culture of these two disciplines is almost inherently integrated due to the effect each has on the other.

2.2 The Analytical Hierarchy Process

The eight points of integration are all qualitative areas with various degrees of overlap between nuclear safety and security disciplines. To understand how much overlap is found among these integration points (and their potential to produce a synergistic effect), these qualitative factors need to be measurable. The analytical hierarchy process (AHP) is a multi-tiered method that uses a pairwise comparison matrix (PCM) to rate criteria within and across each tier. Through this process, the qualitative data of the eight integration points can be quantified according to their importance for nuclear safety and security integration. The quantified points can then be analyzed and provide weights of importance for each integration point.[11]

A survey tool was provided to nuclear professionals who worked in research reactors and associated facilities (RRAF) and were familiar with the nuclear safety and security disciplines. In the survey, participants were asked to compare each integration point against the other points regarding their comparative importance for integration. The comparisons utilized the fundamental nine-point scale designed by Saaty for the AHP (Table 1).[11] The aggregated results were then analyzed accordingly.

Table 1: The Fundamental Scale for AHP (in evaluating points of integration between Nuclear Safety and Nuclear Security)[11]

Importance for Integration	**Definition**	**Explanation**
1	Equal importance for integration	Two comparisons have equal importance when considering the respective potentials for integration.
3	Moderate importance for integration	One activity is considered moderately more important for integration when compared to the other activity.
5	Strong importance for integration	One activity is strongly considered more important for integration when compared to the other activity.
7	Very strong importance for integration	One activity is very strongly considered more important for integration when compared to the other activity.
9	Extreme importance for integration	One activity is considered of the highest importance for integration when compared to the other activity.
2, 4, 6, 8	Intermediate values between relative adjacent potentials	Use when one activity has a consideration of importance that lies between one of the above values.
Reciprocals	When value *i* has been assigned to one of the numbers above, then value *j* has the reciprocal in the PCM.	One activity is of less importance, comparable to its reciprocal in the PCM.

The quantified importance and response inconsistency were evaluated using a PCM for each participant. Inconsistency of the participant PCM was determined by calculating each matrix's consistency index (*CI*)—the *CI* was calculated using the number of matrix elements (*n*) and the maximum eigenvalue of the matrix (λ). The consistency ratio (*CR*) was then determined by comparing the ratio of the *CI* and Saaty's random consistency index (RI). The random consistency index (RI) is a predetermined value explicitly used for the AHP based on *n* (Table 2).

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (1)$$

$$CR = \frac{CI}{RI} \quad (2)$$

Saaty recommends a maximum CR of 0.1. This indicates the inconsistency of the participant responses is a maximum of 10%. Higher inconsistency values infer the data will be less likely to replicate and decrease potential validity.[11]

Table 2 – The Random Consistency Index[11]

n	≤2	3	4	5	6	7	8	9	10
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

2.3 Monte Carlo Simulation

The AHP has been an influential and validated method for converting qualitative data into measurable, quantitative results. It has been used across many fields of study, including economics, agriculture, and ecological studies. Through the many years and disciplines, an additional method has developed to improve upon the results of the AHP. Applying a Monte Carlo simulation is a method that has improved the results found through the AHP methodology.

The AHP is a complex process with an average number of participants ranging from five to ten. The small population displays a lack of statistically significant data. Also, judgment uncertainty can interfere with the quantified results as some participants may rate more than one criterion with equivalent importance. For this study, judgment uncertainty introduced difficulty in determining the range of importance among the integration points being evaluated.

The most effective method for overcoming judgment uncertainty and increasing statistical significance is incorporating a Monte Carlo (MC) simulation. Jing et al.[12] utilized the analytical hierarchy process with an assisted Monte Carlo simulation (AHP-MC) to determine the most effective method for addressing non-point source pollution in China. In their study, the MC simulation utilized a beta-Project Evaluation and Review Technique (PERT) distribution that triangulated their data (focusing on the mean, minimum, and maximum values). Using an MC simulation with a beta-PERT distribution improved their result accuracy and decreased judgment uncertainty. This study also applied an MC simulation with a beta-PERT distribution to the participant responses. The beta-PERT distribution requires calculating the mean, standard deviation, alpha, and beta values. Those calculations required the minimum, maximum, and modal responses to be determined among all the participant responses, where *p* is the number of participants (equations 3, 4, 5, and 6).

$$mean = \frac{min + 4modal + max}{p} \quad (3)$$

$$SD = \frac{max - min}{p} \tag{4}$$

$$\alpha = \left(\frac{mean - min}{max - min}\right)\left(\frac{(mean - min)(max - mean)}{SD^2} - 1\right) \tag{5}$$

$$\beta = \left(\frac{max - mean}{mean - min}\right) \cdot \alpha \tag{6}$$

Utilizing MATLAB, the MC simulation performed 1,000 iterations of the non-diagonal values for all PCM based within the calculated beta-PERT distribution. The diagonal responses were determined as the reciprocals of the input data (per the AHP methodology), producing a matrix equation (7) that would allow the calculation of integration point importance and consistency ratios.

$$\begin{array}{c} \\ I_1 \\ I_2 \\ I_3 \\ \vdots \\ I_8 \end{array} \begin{array}{c} \begin{array}{ccccc} I_1 & I_2 & I_3 & \dots & I_8 \end{array} \\ \begin{bmatrix} 1 & a_{12} & a_{13} & \dots & a_{18} \\ 1/a_{12} & 1 & a_{23} & \dots & a_{28} \\ 1/a_{13} & 1/a_{23} & 1 & \dots & a_{38} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1/a_{18} & 1/a_{28} & 1/a_{38} & \dots & 1 \end{bmatrix} \end{array} \tag{7}$$

The MC simulation scores were aggregated with the sum of the weighted criteria and compared for final analysis, where A_k is the final score (to the kth alternative), b_{kj} is the score according to the kth alternative, and the jth integration point, W_j is the normalized weight of the jth integration point (equation 8).

$$A_k = \sum_{j=1}^{8} \left(b_{kj} \cdot W_j\right) \tag{8}$$

Once all values and consistency ratios were calculated within the MC simulation, a probability distribution function (pdf) was calculated and used to determine the range of quantified importance among all integration points.

3. Results and Discussion

Four participant responses had a calculated CR under 0.1; two participants had a CR under 0.15. For purposes of this study, it was determined that a CR under 0.15 would be acceptable. Of the six participants, three rated defense in depth as the most important for integration, two rated culture as most important, and one rated access control and transportation as equally the most important points. When calculating the average of all weighted integration points, it was found that transportation of materials was the most important for integration. Evaluation of the aggregated individual survey responses for statistical significance found the confidence intervals of the quantified importance ranges to be very wide, indicating a potential reason for the variation for the most important point.

The participant results were applied to the MC simulation (using a beta-PERT distribution) to better determine the importance of each point when considered for integration in an RRAF. The MC simulation ran 1,000 iterations within these parameters, and a pdf was calculated to visualize the range of quantified importance for each point. This method determined access control to be the most important point for integration, followed by transportation of material and proper disposal of waste material (see Fig. 1).

These results demonstrate how applying a Monte Carlo simulation to the individual AHP results can elucidate data that would otherwise have gone unnoticed. If the individual results were taken at face value, transport of materials would have been considered the most important integration point according to the average of all six responses. However, looking closely at the statistical analysis of the individual responses, considerable overlap can be observed in the confidence intervals of the average point importance—demonstrating a significant level of judgment uncertainty regarding the true location for each point in the range of importance (see table 3a).

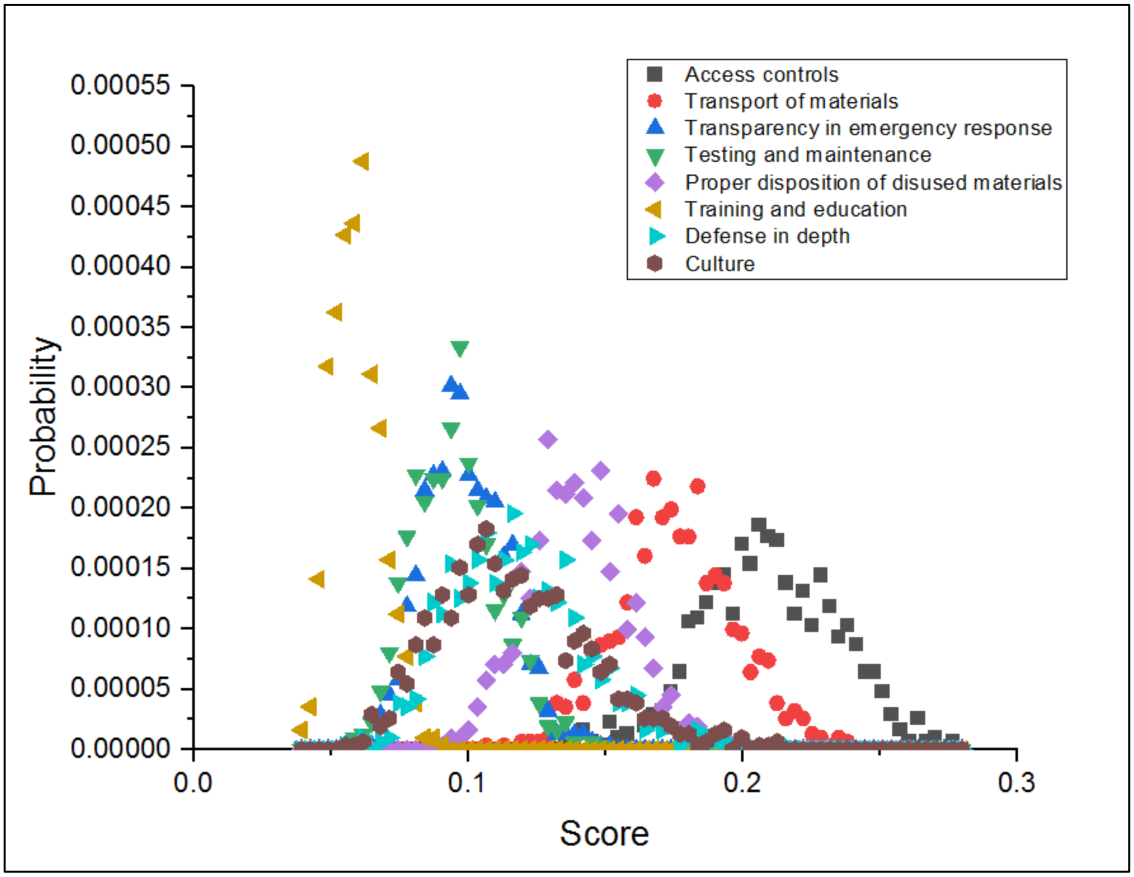

Figure 1. Probability density of the MC simulation importance ratings for all integration points.

Table 3(a): Individual Weighted Scores

	Mean *($x10^{-2}$)*	*Standard Dev.* *($x10^{-2}$)*	*Variance* *($x10^{-2}$)*	*CI (Lower 95%)* *($x10^{-2}$)*	*CI (Upper 95%)* *($x10^{-2}$)*
Access controls	14.576	8.216	0.675	5.954	23.198
Transport of Materials	27.020	10.445	1.091	16.059	37.981
Transparency in Emergency Response	8.081	2.425	0.059	5.536	10.626
Testing and Maintenance	10.827	4.946	0.245	5.636	16.018

Proper Disposal of Materials	10.314	4.183	0.175	5.924	14.703
Training and Education	7.525	5.144	0.265	2.127	12.923
Defense in Depth	16.295	9.411	0.886	6.419	26.171
Culture	18.872	11.416	1.303	6.891	30.852

Table 3(b): MC Simulation Weighted Scores

	Mean ($x10^{-2}$)	*Standard Dev. ($x10^{-2}$)*	*Variance ($x10^{-3}$)*	*CI (Lower 95%) ($x10^{-2}$)*	*CI (Upper 95%) ($x10^{-2}$)*
Access controls	20.746	2.458	0.060	20.594	20.899
Transport of Materials	17.393	2.113	0.045	17.262	17.524
Transparency in Emergency Response	9.754	1.486	0.022	9.662	9.846
Testing and Maintenance	9.376	1.537	0.024	9.281	9.472
Proper Disposal of Materials	13.796	1.815	0.033	13.684	13.909
Training and Education	5.797	0.866	0.008	5.743	5.850
Defense in Depth	11.637	2.427	0.059	11.487	11.788
Culture	11.499	2.725	0.074	11.330	11.669

When considering the MC simulation's statistical analysis, each integration point's quantitative importance becomes more transparent and precise. With this data set, no overlap of confidence intervals is observed, and access control becomes the integration point of most importance. It would not have been possible to observe the trend in this data without applying the MC simulation.

This study defined access control as the selective restriction of access to a place or other resources. Integration is found in this point as it prevents accidental radiation exposure and protects the target material from malicious attackers by implementing authorized access. Conversely, a lack of integration can be observed when access control is lost. In the investigations of the Fukushima-Daiichi nuclear power plant accident, it was discovered that safety failures created by the chain of events degraded access to critical plant infrastructure. The lack of access control prevented entry to critical locations and allowed entrance to areas that should have remained unavailable.[13] The ability to maintain control of essential access points was lost, compromising safety and security. Applying an integrated risk management approach to access control can assist in identifying both safety and security deficiencies, thereby increasing the chance of mitigating and preventing future complications.

4. Conclusion

Integration of nuclear safety and security is essential for accurately assessing risk estimates in a facility. By only considering the risk estimate of one discipline, the facility's risk is underestimated, and vulnerabilities can be exploited. Research reactors have a unique level of vulnerability when considering their footprint and the nuclear material used in their facilities. Even though the footprint is smaller than a nuclear power plant, it provides an analog for larger reactors' safety and security practices that can be more quickly implemented and analyzed before transferring to a power-size reactor. The new SMR are an even closer analog to the safety and security footprint observed in a research reactor. By finding methods for improving safety and security in an RRAF, we can more easily implement improvements in the radiation protection programs of power reactors and other fields of nuclear and radiological operations.

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