

■ Article

Challenges and Strategies for the Standardization of WANO Best Practices in Japan, China, and South Korea

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Abstract

This chapter examines how the World Association of Nuclear Operators (WANO) “best practices” can be adopted and partially harmonized across Japan, China, and the Republic of Korea, and why such harmonization remains challenging in East Asia. Conceptually, best practices are treated as portable, performance-oriented routines anchored in WANO’s Performance Objectives and Criteria (PO&C). Empirically, the study compares national adoption pathways in two core mechanisms—operating experience feedback and the systematic approach to training (SAT)—using the United States as a benchmark case. Drawing on document analysis of international guidance and national regulatory and industry materials, the article identifies three structural barriers to regional convergence: institutional divergence in regulatory autonomy and transparency; technical discontinuities associated with reactor type, generational differences, digital I&C systems, and aging or first-of-a-kind (FOAK) management; and political constraints rooted in public trust, policy volatility, and sovereignty-sensitive attitudes toward international standards. To complement the institutional analysis, a descriptive comparison of selected reactor units’ operating performance (EAF/FLR) is used to illustrate how “event-year” responses—shutdown, diagnosis, corrective action, and recovery—translate institutional logics into observable operating patterns. The findings suggest that East Asia already shares a practical foundation in OE and SAT structures, but that meaningful convergence requires converting plant-specific lessons into standardized “experience types” and embedding them into domestic risk assessment and training cycles. The article proposes a staged regional strategy centered on a low-politics OE case library, modular SAT-based co-training, and standing technical working groups on FOAK stabilization and aging management.

Keywords: WANO; East Asia; Best Practices; EAF/FLR; Nuclear Regulation; Nuclear Safety Standardization; Operational Experience; Institutional Harmonization; Regional Nuclear Governance; Systematic Approach to Training

I. Introduction

International nuclear safety governance has evolved through a layered architecture combining intergovernmental standards, legal instruments, and industry-led self-regulatory mechanisms. Since the 1960s, the International Atomic Energy Agency (IAEA) has developed an extensive body of safety standards and promoted legal frameworks such as the Convention on

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Nuclear Safety, providing Member States with common technical references for regulatory development and nuclear power plant (NPP) operation. However, these standards remain largely non-binding unless incorporated into domestic law, and their effectiveness depends heavily on national institutional capacity, regulatory autonomy, and political commitment. As a result, significant cross-country variation persists in enforcement intensity, transparency, and continuous improvement practices.

Alongside intergovernmental frameworks, industry self-regulation has expanded, most notably through the World Association of Nuclear Operators (WANO). Established in 1989, WANO seeks to strengthen nuclear safety through peer reviews, operating experience (OE) feedback, benchmarking, and training initiatives. Central to this architecture are WANO “best practices” and the Performance Objectives and Criteria (PO&C) framework. While PO&C provides a structured reference for performance expectations and self-assessment, best practices represent curated, field-tested approaches for improving performance. In practice, OE processing and training-related routines serve as key channels through which operational lessons are prioritized, shared, and embedded beyond formal regulation.

Following the Fukushima Daiichi accident in 2011, regional harmonization of nuclear safety baselines has gained renewed attention, particularly in East Asia. Japan, China, and the Republic of Korea collectively account for a substantial share of global nuclear capacity and are active participants in WANO activities. Yet their nuclear governance systems differ markedly in regulatory arrangements, transparency norms, safety culture, and public trust. While all three countries formally participate in WANO peer reviews and OE mechanisms, implementation remains fragmented across institutional, technical, and political dimensions. This raises a core policy-relevant question: within a global nuclear safety architecture shaped jointly by IAEA standards and WANO self-regulation, how can Japan, China, and the ROK adopt and localize WANO best practices in ways that enable substantive—though necessarily partial—regional harmonization? In this study, “partial” harmonization refers to achievable alignment in (i) shared taxonomies for classifying lessons and issues, (ii) interoperable interfaces for exchange and coordination, and (iii) the embedding of lessons into routine organizational decision processes.

This study addresses this question by placing WANO best practices and PO&C as reference points for a comparative institutional analysis. Using the United States as a benchmark for institutionalized OE and Systematic Approach to Training (SAT) mechanisms, the article examines how best practices are identified, stabilized, and embedded in routine operations, and how adoption pathways differ across Japan, China, and the ROK. By integrating institutional analysis with descriptive operating performance indicators, the study evaluates the feasibility and limits of regional harmonization and develops staged, domain-specific policy recommendations for East Asia. The performance indicators are used to contextualize mechanism–performance linkages rather than to construct a direct ranking of national “safety.”

II. Theoretical foundation and analytical framework: WANO best practices and the partial harmonization of nuclear safety baselines

II.1 Concept and defining features of WANO “best practices”

Unlike the IAEA Safety Standards, WANO does not publish a fixed, exhaustive “best practice list.” In WANO’s institutional design, best practices are not static provisions but an evolving body of operational experience that is continuously identified, validated, and updated through multiple channels, such as operating experience products, peer review observations and recommendations, cases shared through technical exchanges, and PO&C-based guidance materials.

In functional terms, a practice can be regarded as a “best practice” when it exhibits at least three features: First, it is aligned with the safety and performance objectives articulated in the WANO’s Performance Objectives and Criteria and demonstrably supports or improves the relevant outcomes. Second, it has been repeatedly validated in more than one plant, shows stable and traceable effects, and is explicitly recognized through WANO-related processes (e.g., peer reviews or OE feedback). Third, it has a degree of transferability, meaning that it can be adopted with appropriate contextual adjustments across plants operating under different national settings and technological pathways.

In other words, WANO best practices are not abstract “ideal states.” They are replicable lessons filtered and validated within specific operational contexts and then shared among members for broader applications. Accordingly, this study defines “WANO best practices” as operational and managerial measures that (i) are referenced against PO&C, (ii) are continuously validated through mechanisms such as peer review, OE, and training, and (iii) have cross-plant and cross-national applicability. This definition serves as a common analytical baseline for subsequent comparisons between Japan, China, and South Korea.

II.2 WANO PO&C: performance objectives and assessment domains

WANO’s Performance Objectives and Criteria serves as a reference structure for articulating expected conditions for safety, reliability, and organizational management. It also provides a shared language for peer review and performance benchmarking, enabling findings and improvement priorities to be mapped onto comparable assessment domains.

To enable a structured comparison in later sections, this chapter distinguishes WANO’s programme carriers from PO&C-based assessment domains. WANO sustains its best-practice regime through four programme areas—Peer Review (PR), Performance Analysis (PA), Training & Development (T&D), and Member Support (MS). Within this architecture, PO&C functions primarily as a PR-anchored reference framework: it specifies relatively stable (yet periodically updated) performance objectives and criteria that structure peer-review observations, benchmarking, and the identification of performance gaps. Operating experience is treated analytically as a PA-centered learning and translation mechanism that cuts across PO&C domains, rather than as a domain in its own right, because it operationalizes learning through event

reporting, screening, analysis, corrective actions, and feedback products that inform both operator practice and regulatory expectations. T&D provides the capability interface through which lessons from PR/PA (including OE products and peer-review findings) are translated into competence requirements, training design, and routine team behaviors, while MS complements these processes through targeted support and dissemination. This programme-level positioning clarifies why the subsequent analysis focuses on the OE–training linkage as a core mechanism for institutionalizing best practices across national settings.

II.3 Theoretical basis of operating experience feedback and the systematic approach to training

Within WANO’s programme architecture, OE feedback is carried primarily through Performance Analysis (PA), while the institutionalization of the Systematic Approach to Training is supported mainly through Training & Development (T&D). Together, they function as two key mechanisms for translating abstract safety objectives into organizational routines and daily practices. They not only support the formation and continuous updating of best practices but also provide institutional carriers for sustaining continuous improvement in safety culture.

The core logic of OE feedback is to establish a learning loop at both the organizational and industry levels by systematically collecting, analyzing, and sharing events and near misses. The IAEA notes that an effective OE program typically includes at least the following elements: information collection, screening and evaluation, causal analysis, development and tracking of corrective actions, dissemination of lessons learned, and effectiveness review (IAEA 2010). Through this cycle, events occurring at a single plant are no longer treated as isolated incidents; instead, they become inputs to shared learning that can drive revisions of operating procedures, equipment modifications, and management systems. In this sense, OE provides an empirical substrate from which best practices can be derived.

OE feedback and SAT together constitute a conversion chain from “experience” to “institution” and ultimately to “capability.” OE supplies facts, signals, and improvement opportunities, while SAT helps ensure that lessons learned are consistently internalized as organizational competence and behavioral patterns. For an industry-led best-practice regime centered on WANO, this chain bridges standard-like frameworks (such as PO&C) with plant-level implementation and underpins the institutional comparisons of the United States and East Asian countries in later sections.

Building on this conversion-chain logic, partial harmonization is defined as a graded outcome of how OE–training linkages travel and stabilize across national settings. Level 1 (taxonomy convergence) is achieved when OE lessons are expressed in sufficiently comparable problem types and terms to support cross-national communication. Level 2 (interface alignment) is reached when key learning gates—screening, prioritization, analysis triggers, and feedback products—are structured so that lessons can be exchanged with limited translation loss. Level 3 (selective embedding) is realized when such aligned interfaces are incorporated into domestic

routines (e.g., training/qualification, monitoring, corrective-action tracking, or inspection emphases), turning shared learning into stable organizational capability. These levels provide an operational metric for evaluating both feasibility and constraints in Chapters 4~7.

II.4 Scope and analytical framework

The core object of analysis is the adoption and operation of WANO best practices and related mechanisms across different institutional environments. This chapter adopts the three-level definition of partial harmonization specified in Section 2.3 and uses it as an organizing device for subsequent cross-national comparison.

The analysis is conducted at three interconnected levels. First, it examines WANO as a transnational industry self-regulatory mechanism and clarifies how best practices, PO&C, operating experience (OE), peer review, and training are designed as a “portable practice package.” Second, it compares how Japan, China, and the Republic of Korea receive, translate, and localize these tools within their domestic nuclear safety institutions and energy-policy contexts. Third, it considers how best-practice adoption manifests at the operator and plant/unit levels, including management routines and observable operational outcomes. U.S. practices around OE and SAT are treated as a benchmark reference for clarifying the conditions under which self-regulatory best-practice mechanisms can operate in a stable and institutionalized manner.

Temporally, the study focuses primarily on the post-Fukushima period, during which East Asian nuclear governance has been reshaped, while selectively tracing key developments in U.S. best-practice institutionalization since the 1980s. Spatially, it centers on commercial reactor units and operating organizations in Japan, China, and the ROK, while drawing on the rules and practices of international organizations and industry associations where necessary. This yields a multi-level analytical object spanning “international mechanisms–national institutions–operational practices–unit performance.”

Conceptually, the study employs a tripartite lens—institutions, technology, and politics/society—to interpret best-practice adoption and prospects for partial harmonization. The institutional dimension emphasizes regulatory independence and consistency, institutionalization of OE and training systems, and domestic interfaces with WANO mechanisms. The technical dimension examines reactor-type composition, design and operational standards, aging management for older units, pathways for new-build introduction, and the comparability of technical standards and implementation practices. The political and societal dimension highlights energy-policy orientation, societal trust and risk perception, accident memory, and external security or diplomatic relations that may shape willingness and pathways for regional cooperation. Together, these dimensions support a structured interpretation of how best practices travel from “international industry mechanisms” to “domestic arrangements” and, ultimately, to “observable operational outcomes.”

II.5 Prior research and research gap

Existing research on nuclear safety governance has largely examined how international regimes and standards shape national regulatory practices. A recurrent finding is that global nuclear safety governance has evolved from a technical-standards-centered model toward a layered architecture combining legal conventions, safety standards, and peer-review-type instruments (Findlay 2011). In this context, the IAEA’s legal and guidance framework—centered on the Convention on Nuclear Safety and associated safety standards—provides widely referenced benchmarks for domestic legislation and regulatory practice, even though formal binding force depends on national incorporation and enforcement capacity. A related strand of scholarship emphasizes that “non-binding” standards may still operate as *de facto* benchmarks through reputational incentives and socialization processes, contributing to cross-national diffusion while leaving substantial variation in implementation.

In parallel, research on industry self-regulation and operating experience feedback frequently treats WANO as a representative case of transnational private governance. Historical accounts highlight how major accidents catalyzed operators’ recognition that “nuclear safety has no borders,” motivating the establishment and subsequent development of WANO (Cantelon 2016). Studies commonly identify WANO peer reviews and operating experience feedback as the backbone of WANO’s continuous-improvement logic and describe a closed-loop learning mechanism—event reporting, screening and analysis, corrective actions, dissemination, and follow-up—intended to stabilize organizational learning across member utilities (Revelta 2004; Mampacy 2008). At the same time, the literature also notes that effectiveness depends on whether member organizations internalize lessons learned and translate them into routine operational practices, rather than merely participating in formal processes.

After the Fukushima Daiichi accident, the literature increasingly addressed institutional failure and safety culture, stressing issues such as regulatory capture, organizational inertia, leadership commitment, and trust repair. Regionally, East Asia–focused discussions often begin from national institutional differences and highlight the role of dialogue platforms such as the Japan–China–Korea Top Regulators Meeting (TRM) and the Asian Nuclear Safety Network (ANSN), while also noting the absence of strongly binding regional arrangements comparable to those in Europe. Commonly cited obstacles include sovereignty sensitivity, uneven regulatory independence and transparency, and the lack of a stable coordination mechanism.

Against this background, three gaps motivate the present study. First, despite growing discussion of WANO and peer review, relatively few studies place WANO best practices and PO&C at the center of a systematic comparative framework that traces how practices are identified, stabilized, and embedded across different national settings. Second, existing cross-national comparisons often remain fragmented in analytical structure and rarely operationalize “partial harmonization” in a way that can be assessed in mechanism-relevant terms. Third, due to limited disclosure of peer-review results, prior work faces methodological constraints in linking WANO-related mechanisms to observable outcomes; while direct causal inference is difficult, a

structured combination of institutional analysis with publicly available performance-oriented indicators can still provide useful contextual evidence for evaluating the plausibility, limits, and policy relevance of partial harmonization pathways. This study aims to address these gaps.

II.6 Methods, data sources, and analytical pathway

Methodologically, this study relies primarily on document analysis and comparative institutional analysis. It reviews normative documents, technical standards, policy reports, and other publicly available materials issued by international organizations, industry associations, and national regulators to reconstruct the institutional logic through which WANO best practices are generated, interpreted, and embedded, and to compare adoption pathways and institutionalization processes in Japan, China, and the Republic of Korea.

The data sources fall into three categories. First, international materials produced by the IAEA and WANO are used to clarify shared reference structures, including safety standards, PO&C documents, operating experience resources, and peer-review-related guidance. Second, national- and organization-level documents from key actors are used to map domestic arrangements and implementation interfaces, including (but not limited to) the U.S. NRC and INPO, Japan's NRA and JANSI, and the relevant regulators and operators in China and the ROK. Third, publicly available unit-level operational performance data released by the IAEA and national sources are used for descriptive cross-unit comparison as supplementary evidence alongside institutional analysis.

Analytically, the paper proceeds from “mechanism reconstruction” to “cross-national comparison,” with performance-oriented evidence informing policy implications. Section 2 establishes the conceptual and analytical foundation for WANO best practices, PO&C positioning, and the OE–training linkage, and specifies the meaning of “partial harmonization.” Section 3 examines the United States as a benchmark case for institutionalized OE and Systematic Approach to Training mechanisms. Section 4 compares the adoption practices and institutional environments of Japan, China, and the ROK. Section 5 synthesizes key obstacles to harmonization across institutional, technical, and political dimensions. Section 6 introduces cross-unit operational indicators to contextualize how institutional differences may leave observable traces in operating outcomes, without constructing a direct ranking of national “safety.” Section 7 proposes staged and domain-specific policy recommendations for regional cooperation.

III. The U.S. nuclear “best-practice” regime: institutionalizing OE and SAT

This section uses the United States as a benchmark case to explain how WANO-style “best practices” are institutionalized and routinized within a domestic nuclear governance system. The United States is selected as a benchmark not as a normative “best” case, but as a mechanism-revealing case in which OE and training are institutionalized through stable interfaces among the regulator (NRC), an industry self-regulatory body (INPO), and WANO. This configuration makes

it possible to trace how heterogeneous signals are triaged, converted into guidance and performance expectations, and then embedded into workforce competence through SAT-type training routines. Moreover, the U.S. case offers relatively rich public documentation, allowing consistent tracing of institutional linkages that are more difficult to reconstruct in other settings. Consistent with the PR–PA–T&D division outlined above, this section treats OE as a PA-centered signal-processing and conversion mechanism, and SAT as a T&D-centered capability interface that embeds lessons learned into routine workforce competence. The emphasis is not on enumerating individual best-practice cases but on identifying the institutional mechanisms that make such practices repeatable and scalable. Drawing on document analysis of publicly available materials from the U.S. Nuclear Regulatory Commission (NRC), the Institute of Nuclear Power Operations (INPO), and WANO, supplemented by relevant academic studies, the section abstracts two coupled modules: operating experience as a signal-processing and conversion mechanism, and the systematic approach to training as a capability interface that embeds lessons learned into workforce competence and routine behavior.¹⁾

III.1 Operating experience as a signal-processing and conversion mechanism

Analytically, the U.S. OE regime can be understood as a conversion chain that links heterogeneous inputs (plant reports, regulatory findings, and international exchanges) to differentiated outputs that shape regulatory expectations and industry learning. The institutional value of OE lies less in “collecting information” than in the ability to (i) triage large volumes of event data, (ii) concentrate attention on common-cause and system-level risks, and (iii) translate selected issues into actionable products, such as updates to review criteria, inspection emphases, guidance, or broadly disseminated communications.

III.1.1 A cross-functional hub linking analysis, licensing, and field feedback

A defining feature of the NRC’s OE arrangement is its cross-functional configuration. Rather than operating as a single, self-contained office, the OE “clearinghouse”-type function is embedded across multiple organizational units and works as a hub that connects technical analysis and risk assessment with licensing/review functions and field inspection feedback. This design increases the likelihood that new OE signals do not remain “archived” within one unit but are routed to institutional levers where regulatory and operational practices are revised.

The cross-departmental roles and information pathways underlying this hub are presented in Table 1. In short, technical functions contribute to analysis and risk insights; licensing and review functions translate OE findings into review criteria and evaluation focuses; regional offices and inspectors provide frontline inputs and implementation feedback; and an OE coordination function organizes information flows, screening meetings, database maintenance, and outward information release.

Table. 1. Organizational structure and cross-departmental coordination in the NRC’s OE clearinghouse²⁾

Participating unit	Role in the OE clearinghouse	Collaboration mode and output direction
Office of Nuclear Regulatory Research (RES)	Technical analysis and risk assessment	Conducts technical/causal analyses of operating events; identifies research issues and risk insights; feeds results into regulatory guidance and related review/inspection bases
Licensing / New Reactor office (e.g., NRO)	Translates OE findings into licensing and review criteria	Adjusts review guidance and technical evaluation bases; revises design review focuses and key review points to reflect OE lessons
Regional offices and onsite inspection staff	Frontline event information and implementation feedback	Submits event reports and field observations; supports implementation of corrective actions; reports implementation effectiveness and field constraints
OE program office / coordination unit	Coordinates information flow and inter-office meetings	Organizes screening meetings; maintains OE databases and tracking; manages outward information release and routine coordination

III.1.2 Division of labor, triage, and tiered outputs

The second feature is the deliberate separation between short-cycle screening work and longer-horizon analytical work. As shown in Table 2, “day-to-day specialists” focus on intake, preliminary screening, and field coordination on the scale of days to weeks, while “analysis specialists” conduct trend analysis, data assessment, and more strategic evaluations over months to years. This division of labor is essential for maintaining analytical depth without overwhelming regulatory attention in the face of high reporting volumes.

Table. 2. Division of Responsibilities between Day-to-Day Specialists and Analysis Specialists.³⁾

	Day-to-Day Specialists	Analysis Specialists
Primary Duties	Event intake, initial screening, onsite coordination	Trend analysis, data evaluation, strategic studies
Time Horizon	Short term (several days to several weeks)	Medium to long term (several months to several years)
Information Handled	Site reports, event notifications, etc.	Archived data, indicator systems, etc.

Building on this staffing logic, the OE workflow operates through a triage and tiered response system. Most items are treated as information for tracking and trend monitoring, while a smaller subset is elevated to issues that warrant broader attention or deeper technical evaluation. Importantly, the outputs are differentiated: higher-significance issues are more likely to generate products that shape regulatory expectations (e.g., revisions to guidance, review emphases, or broadly disseminated communications), whereas lower-significance items primarily support internal monitoring and contextual awareness. Together, triage and tiered outputs serve two functions: they prevent limited resources from being diluted by low-risk noise and increase the probability that systemic risks are recognized and translated into concrete changes, thereby creating stable inputs for subsequent training updates and industry-level learning.

III.1.3 External interfaces: NRC-INPO linkage and international exchange channels

The robustness of U.S. OE regime also depends on institutionalized external interfaces. Domestically, information exchange between the NRC and INPO enables bidirectional learning across regulators and industries: industry-side experience data and trend insights can inform regulatory screening and prioritization, whereas NRC evaluation outcomes can feed back into industry learning products. Internationally, participation in anonymized exchange arrangements—most notably the International Common-Cause Failure Data Exchange (ICDE)—extends the evidence base for validating OE signals and comparing failure modes across jurisdictions. Figure 1 summarizes these domestic and international interfaces and highlights how they support both national learning and internationally transferable mechanism-level knowledge.

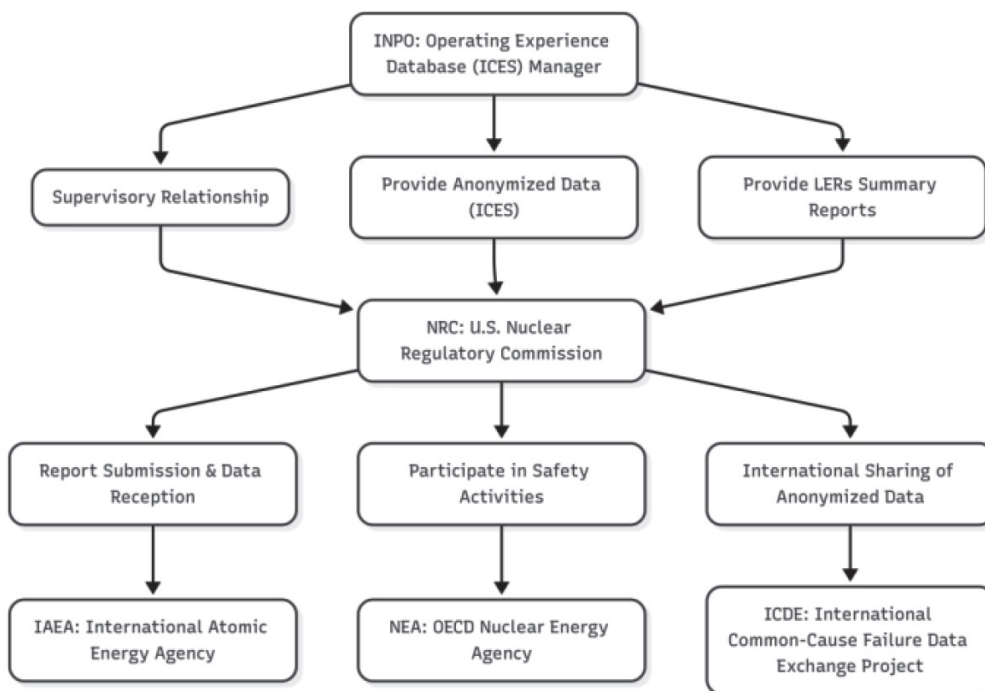


Fig.1 External interfaces of U.S. operating experience information sharing: domestic NRC-INPO linkage and international exchange channels (e.g., ICDE).

III.2 SAT as the capability interface that embeds OE lessons into routine performance

While OE provides signal processing and conversion functions, SAT provides a stable institutional interface for converting selected lessons into workforce capability. In this sense, SAT should not be treated as a purely pedagogical tool. It operationalizes organizational learning by linking experience-derived issues to job requirements, training design, qualification management and recurrent learning. The SAT logic is commonly represented as a closed-loop methodology—analysis, design, development, implementation, and evaluation—through which training is derived from task requirements and revised in response to performance feedback. This closed-loop structure is particularly important for best-practice diffusion: when the OE identifies a recurring

risk pattern or systemic vulnerability, training needs and qualification standards can be updated within an established framework rather than through ad hoc decisions.

U.S. practice suggests that effective SAT implementation depends on an enabling institutional package with three, mutually reinforcing elements. First, management commitment and governance integration: executive backing is needed to secure resources and time, and training outcomes are typically linked to qualification and performance management. Cross-functional governance, which links training, operations, and safety functions, helps ensure that training is treated as part of routine safety management rather than as a peripheral activity. The second is professional support and standardization tools. Subject-matter experts with field experience participate in task analysis, curriculum design, and evaluation, while standardized templates and guidance reduce dependence on individual intuition and improve comparability across sites. Third, integration across training modalities and qualification management is required. SAT is implemented through combined approaches, such as on-the-job training, simulator-based exercises, and periodic re-qualification. Scenario-based assessments and recurrent reviews help ensure that competence evolves with equipment modifications, procedure changes, and accumulating OE lessons.

III.3 Benchmark implications for East Asia

The U.S. case indicates that “best practice” is not a single instrument but a coupled mechanism of organizational learning and capability building. OE provides a structured process for triaging heterogeneous experiences into prioritized issues and tiered outputs, and SAT provides the institutional interface that embeds selected lessons into competence requirements and routine performance through training and qualification. As a benchmark for East Asia, three mechanism-level implications are particularly important.

First, at the “input” end, a cross-functional hub is necessary to connect technical analysis, licensing/review, and field feedback so that experience is routed to institutional levers rather than being treated merely as a reporting obligation. Second, at the “conversion” stage, triage and tiered outputs help concentrate limited attention on common causes and systemic risks and provide clear triggers for revising guidance, reviewing emphases, and training content—thereby avoiding purely formalistic reporting. Third, at the “output” end, OE–training coupling is indispensable: without a capability interface like SAT that converts lessons into competency requirements and recurrent qualification, best practices tend to remain “lessons written in reports” rather than reproducible routines.

These implications should not be interpreted as a call for direct institutional transplantation. The U.S. configuration is embedded in specific historical trajectories, regulatory arrangements and industry structures. Nevertheless, the coupled OE–SAT mechanism offers a clear analytical yardstick for examining how WANO-related best-practice mechanisms are adopted, adapted, and institutionalized in Japan, China, and South Korea in later sections.

IV. Status and Analysis of Best Practice Introduction in Japan, China and South Korea

This chapter compares Japan, China, and the South Korea as national pathways of adopting WANO best practices. For clarity, each subsection ends with a one-sentence placement using the three-level metric (taxonomy–interface–embedding).

IV.1 Japan: institutional independence and deepening practice

After the Fukushima Daiichi accident, a core diagnosis within Japan’s nuclear sector was that the problem was not limited to technical defenses or regulatory design; it also reflected an operator mindset centered on meeting minimum regulatory requirements rather than proactively learning from external experiences and tightening standards beyond compliance. In response, a key post-Fukushima proposition emerged: operators should pursue excellence beyond the legal baseline through industry-led self-improvement, peer pressure and continuous performance enhancement (Japan Nuclear Safety Institute 2023). This orientation is institutionally embodied in the establishment of the Japan Nuclear Safety Institute (JANSI) in November 2012, which was conceptually informed by the U.S. INPO model is positioned as a neutral platform for industry self-regulation. Importantly, “self-regulation” does not replace government regulation; it complements state oversight by creating an internal mechanism for shared expectations, mutual scrutiny, and continuous improvement among operators.

From an institutional perspective, Japan’s post-Fukushima governance can be characterized as a dual structure: an independent regulator on the state side and an industry organization on the self-regulatory side. The analytical significance of JANSI lies in its role as a mechanism that translates international best practice expectations—particularly those associated with WANO peer review and PO&C—into domestic operational standards, diagnostic routines, and improvement support. Over time, JANSI formalized its toolset and procedures, establishing routinized peer-review and integrated assessment practices. Such institutional development can be interpreted as Japan’s attempt to build a stable “self-strengthening” capacity within the industry, enabling operators to benchmark, diagnose, and correct performance gaps under a shared domestic framework while remaining oriented to international expectations.

To clarify the internal logic of this “self-strengthening” capacity, it is useful to distinguish two mutually reinforcing pillars. The first is a domestic translation mechanism in which WANO-related expectations are converted into plant-applicable evaluation points and an iterative improvement cycle centered on peer review. The second is capability deepening and continuous embedding, through which translated expectations are stabilized as organizational routines (especially in human performance) and sustained between peer reviews via continuous performance monitoring aligned with WANO ePM.

Domestic translation mechanism: peer review and an “excellence” cycle

Japan’s best practice adoption is most visible in the domestic translation of WANO-related expectations into an improvement cycle centered on peer review. JANSI operationalizes international expectations by converting them into context-specific evaluation points and performance expectations that are applicable at plant sites. Peer reviews then provide systematic diagnoses across major functional domains, producing areas for improvement (AFIs) that are tracked over time and compared across operators. Crucially, peer review is not treated as a one-off “scoring” exercise; it is embedded in an iterative loop of target setting, evaluation, tailored support, and re-evaluation. Where persistent weaknesses are identified relative to peer performance, JANSI can encourage operators to request focused support, thereby institutionalizing peer pressure as a driver of learning and reform. In terms of mechanism, the “excellence pursuit” logic lies in turning benchmarking and diagnosis into repeatable organizational routines and coupling them with support functions so that identified gaps can be closed systematically rather than left to ad hoc discretion (JANSI 2023). However, translation through peer review is only the starting point: without sustained capability building and monitoring between review cycles, improvement risks remaining concentrated in AFI reporting rather than becoming durable organizational routines.

Capability deepening and continuous embedding: safety culture and PMCM aligned with WANO ePM

Building on the peer-review-centered translation cycle above, the second pillar concerns how translated expectations are internalized as organizational capability and continuously reinforced over time—especially in human performance and performance monitoring. JANSI has treated safety culture as a recurring diagnostic object rather than an abstract slogan, focusing on the organizational climate, decision-making patterns, and learning routines that shape long-term performance. In parallel, team performance enhancement, particularly through simulator-based, scenario-rich training, translates “human performance” expectations into observable team behaviors (e.g., communication, coordination, and disciplined use of human-performance tools). These initiatives matter for best-practice institutionalization because they shift the unit of adoption from “documents and procedures” to “repeatable behavioral routines.”

Most importantly, to sustain improvement between peer reviews, Japan has developed a performance monitoring and continuous monitoring mechanism (PMCM) designed to interface with the WANO’s enhanced performance monitoring (ePM) system. By routinely collecting performance indicators and operational signals into a unified database, PMCM enables trend tracking between review intervals and supports the early identification of abnormal fluctuations or persistent weakening patterns. When such signals arise, the mechanism provides an early warning and encourages special analysis or support before the next formal review, thereby strengthening the continuity of learning and intervention over time. Through linkage with WANO benchmarking,

PMCM also enables domestic comparisons to be interpreted against international baselines, turning best practice adoption from an intermittent “import of standards” into a data-driven, continuous embedding process. As a benchmark for East Asia, Japan’s experience suggests that deepening best-practice adoption depends on coupling (i) a domesticated peer-review cycle that generates actionable AFIs and support, with (ii) continuous monitoring that stabilizes learning and early intervention across time (JANSI 2023).

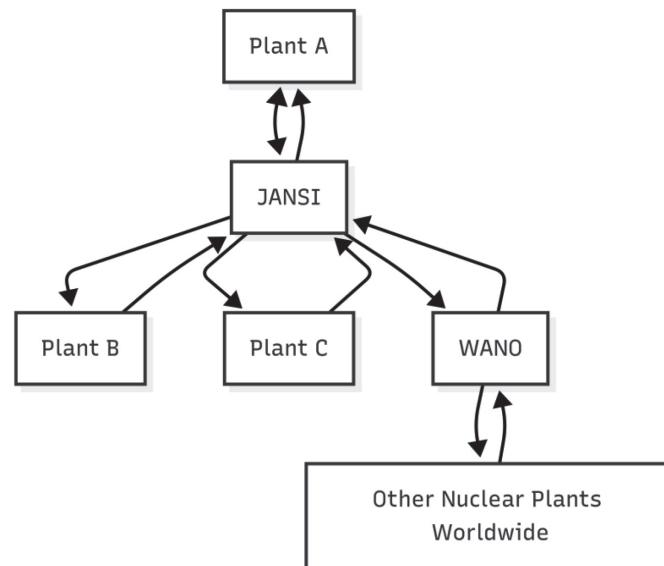


Fig.2 Collaborative Structure of the PMCM Mechanism

In the three-level metric, Japan is between Level 2 (interface alignment) and Level 3 (selective embedding): WANO/PO&C expectations are routinized via JANSI peer review and reinforced through PMCM–ePM monitoring, while the remaining gap is to standardize cross-operator “problem types” and translate AFIs/OE insights into stable, shared training and qualification routines.

IV.2 China: expansion-driven governance and state-embedded institutional practice

IV.2.1 Expansion context and motives for adopting best-practice mechanisms

China’s nuclear power program has expanded from an early phase of technology importation to increasingly localized capabilities in design, construction, and operation. By mid-2019, China operated 47 nuclear power units and had 11 under construction, indicating both a sizable operating fleet and a continuing construction pipeline (SCIO 2019). This scale-up matters analytically because it amplifies the classic “growth–governance gap” in nuclear safety: regulatory capacity must keep pace with fleet growth; operating experience must be accumulated and shared in ways that reduce fragmentation; and workforce development must stabilize human performance under rapid expansion.

In the post-Fukushima period, China framed nuclear safety as a long-term national objective, emphasizing safety culture and capacity building, and conducted nationwide safety

inspections and corrective actions (SCIO 2019). Under these conditions, adopting internationally circulated standards and industry mechanisms is not only reputational benchmarking; it also functions as a governance response to scale-induced risk. Aligning domestic oversight and operator practices with IAEA/WANO-related expectations helps stabilize safety assurance during expansion, enhance international credibility, and support performance benchmarking. At the same time, external assessments suggest that continuous improvement remains salient, particularly in data-driven management and the institutionalization of learning routines across organizations (Schneider & Froggatt 2023). Taken together, “expansion pressure” and “benchmarking ambition” constitute the central drivers of best-practice institutionalization in China.

IV.2.2 Institutional pathways: regulatory embedding, platform-based OE, and SAT-oriented capability building

China’s adoption pathway can be characterized as expansion-driven, state-embedded, and chain-structured: best-practice elements enter primarily through regulatory routines, are converted into cross-organizational learning via a national OE platform, and are stabilized through capability-building arrangements. Here, “state-embedded” is used in a strong sense—not merely indicating the presence of government regulation, but describing an implementation architecture in which (i) licensing, supervision, and verification serve as the main entry point for embedding externally emphasized elements into baseline obligations, and (ii) a regulator-linked national OE platform functions as the principal vehicle for cross-organization learning under rapid fleet growth. This differs from pathways that rely more heavily on industry-led self-regulation and peer-pressure cycles as the primary translation mechanism (as in Japan). Figure 3 summarizes this mechanism chain and its main interfaces (see Fig. 3).

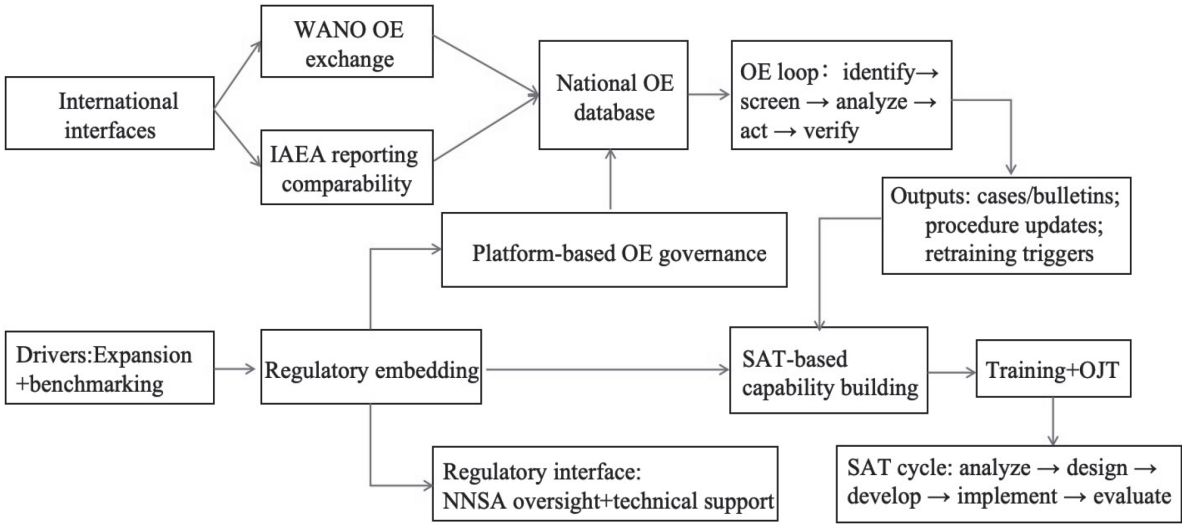


Fig.3 China’s expansion-driven, state-embedded pathway for adopting best-practice mechanisms⁴⁾

First, best-practice expectations are institutionalized through regulatory embedding.

China's nuclear safety regulation is coordinated by the National Nuclear Safety Administration (NNSA) and supported by technical support organizations that provide assessment and verification functions (NNSA 2023). The analytical emphasis here is not on organizational labels but on the existence of a stable institutional interface through which externally emphasized elements—such as OE, safety culture, and emergency preparedness—can be embedded into domestic regulatory routines. Staged licensing and continuous supervision across the facility lifecycle provide a procedural pathway to integrate such elements into baseline obligations and oversight priorities (SCIO 2019; NNSA 2023). From a comparative perspective, this state-centered interface differentiates China from pathways that rely more heavily on industry self-regulation to diffuse best practices.

Second, China institutionalizes organizational learning through platform-based OE governance. China has established a nationwide OE information platform (covering nuclear power plants and research reactors), consolidating event reports, operational anomalies, and external experiences into a unified database environment (SCIO 2019; NNSA 2023). This platform operationalizes the closed-loop logic emphasized in international OE guidance—identification, screening, analysis, corrective action, and verification/feedback (IAEA 2010). In practice, it supports graded reporting and response for events above defined thresholds, facilitates cross-organizational sharing among operators, regulators, and technical support bodies, and generates learning-oriented outputs (e.g., bulletins and typical cases) that can trigger retraining and procedural updates (NNSA 2023). International interfaces primarily reinforce this OE pillar: Chinese operators participate in WANO OE exchanges and engage in IAEA-related activities that enhance comparability in reporting and analysis (NNSA 2023). The key implication is that learning is not confined to firm-level routines; the national platform reduces fragmentation across a growing and heterogeneous fleet, while international interfaces expand the evidence base and strengthen benchmarking and verification.

Third, capability building increasingly serves as the translation layer from learning to stable performance. Chinese operators generally maintain multi-layer training systems—pre-job training, on-the-job training, and periodic re-qualification—supported by plant training centers, full-scope simulators, and qualification management practices (NNSA 2023). In recent years, SAT-oriented approaches have been introduced to structure training as a closed loop of needs analysis, design, development, implementation/assessment, and evaluation. SAT matters here because it provides a learning–capacity interface: OE outputs, peer-review insights, and internal event analyses can be translated into competence requirements and updated training content, turning lessons learned into repeatable routines rather than episodic documentation (IAEA 2010). However, as in many rapidly expanding systems, the maturity and consistency of OE–training–qualification coupling may vary across organizations and units—an issue that becomes salient when assessing implementation quality under expansion and heterogeneity (Schneider & Froggatt 2023).

Overall, China has developed a coherent pathway for adopting best-practice mechanisms under expansion pressure: regulatory embedding provides a stable interface for institutional

absorption, platform-based OE governance supports closed-loop learning across organizations, and SAT-oriented capability building helps stabilize learning outcomes as organizational competence. The critical issue for comparative evaluation is therefore less the existence of formal mechanisms than the consistency and maturity of implementation across organizations and units, especially regarding data-driven management and the stable coupling between OE insights and training/qualification systems.

In the three-level metric, China sits between Level 2 (interface alignment) and Level 3 (selective embedding): regulatory routines and the national OE platform provide a strong learning interface, while embedding into stable, cross-operator training/qualification cycles remains uneven under rapid expansion.

IV.3 South Korea: Institutional foundations and practice features behind high performance

South Korea's comparatively strong operating performance is often attributed to engineering choices and disciplined execution. From an institutional perspective, however, the more relevant question for this chapter is how learning is stabilized—namely, how operating experience is translated into traceable corrective actions, design/program updates, and workforce capability. This section highlights three mechanisms: (i) a regulator–technical support–operator chain that clarifies responsibilities for analysis and implementation; (ii) a closed-loop OE system centered on corrective action tracking; and (iii) aligned learning interfaces linking OE to human factors engineering (HFE) and training.

IV.3.1 Regulatory chain and safety culture as an assessable variable

Korea's safety governance can be understood as a functionally differentiated but coordinated chain: regulatory decisions are coupled with technical reviews and plant-level execution, with training/certification functions linked to competency maintenance. Analytically, such a chain reduces ambiguity about who evaluates events, mandates corrective actions, and verifies closure—conditions that allow OE to operate as a disciplined learning loop rather than a reporting formality.

Within this configuration, safety culture is not treated as an abstract ideal but as an assessable variable embedded in structured routines. Methodological work on safety culture impact assessment in Korea reflects efforts to operationalize safety culture in evaluative terms (Han and Jae 2014). This matters because many WANO-related best practices rely on “soft” organizational traits (e.g., conservative decision-making, reporting norms, procedural compliance) that become consequential only when they are incorporated into recurring assessment and feedback cycles. In addition, Korea's practice is often described as combining internal self-assessment with external review—i.e., a dual-track approach to safety culture evaluation—providing an institutional channel through which cultural signals can be translated into managerial

and corrective actions (Kim, Kim, and Lee 2008).

IV.3.2 OE institutionalization: traceability, HFE feedback, and capability conversion

A distinguishing feature of Korea's OE practice is its emphasis on traceability throughout the OE lifecycle. The development of the Corrective Action Tracking System (CATS) explicitly addresses the problem of ensuring that OE findings and recommendations are not only recorded but also implemented, followed up, and verified for effectiveness (Kim, Kim, and Lee 2008). From a best-practice perspective, this traceability makes learning observable and auditable, enabling both regulators and operators to differentiate documentation from genuine institutionalization.

Korea's OE practice also exhibits a strong interface with human factors and with design/program improvement. In APR1400-related documentation, operating experience is screened and curated to identify recurrent issues, and HFE-relevant discrepancies are translated into managed items that support resolution and verification processes (KEPCO and KHNP 2014). This implies a design-feedback function: OE is used not only to correct deviations in existing plants but also to inform systematic refinements in new-build programs, thereby strengthening inter-generational learning.

Finally, Korea's improvement logic is reinforced by indicator-oriented programs. A framework for improving safety performance indicators provides a complementary channel through which OE trends can be interpreted as performance signals, supporting prioritization and continuity of follow-up (Lee 2001). Training then functions as the capability endpoint of the learning chain. Evidence from Korea's SAT-based training design—especially in specialized domains such as decommissioning—shows how SAT can structure training needs analysis, course development, and evaluation in a standardized and auditable manner (Kwak 2016). Although domain-specific, the analytical implication is transferable: SAT-style cycles provide a stable interface for absorbing OE updates into competency requirements and training content.

In summary, Korea's case suggests that sustained high performance is supported by a coherent mechanism chain: coordinated governance interfaces, a traceable OE loop (CATS), an HFE/design-feedback pathway, and a training structure that can institutionalize lessons learned. For the comparative argument of this chapter, the key is not the sheer number of tools but the degree to which learning mechanisms are coupled and routinized across regulation, analysis, implementation, and capability development.

In the three-level metric, South Korea sits close to Level 3 (selective embedding): aligned learning gates (screening, corrective-action tracking, and HFE/training interfaces) are coupled to traceable closure and capability conversion, while the remaining challenge for regional convergence is making taxonomies and exchange formats sufficiently interoperable for low-loss cross-border learning.

V. Three Key Challenges in Achieving Common Best Practices Among China, Japan, and South Korea

The standardization of WANO best practices aims to elevate safety standards and ensure operational consistency across the global nuclear power industry. However, significant obstacles persist in achieving such standardization in China, Japan, and South Korea due to structural differences in institutional frameworks, political landscapes, and technological approaches. This section categorizes these barriers to commonality into three dimensions and provides an analysis.

V.1 Institutional constraints

Institutional harmonization in East Asia is constrained less by the absence of safety concepts than by the uneven capacity to routinize best practices into clear, interoperable, and externally legible domestic rules. In the three-level metric, institutional constraints primarily bind Level 3 (selective embedding), because weaknesses in regulatory autonomy, coordination, and professional routines limit the stable domestication of aligned OE–training interfaces into everyday organizational practice.

Japan faces an “interface problem”: post-Fukushima governance strengthened oversight, yet recent lifetime extension reforms reveal procedural ambiguity (e.g., interpretive disputes around outage treatment), which delays regulatory convergence and complicates cross-border comparability (Murakami 2024). In parallel, where industry-led improvement mechanisms operate alongside state regulation, unclear boundary management can increase coordination costs and slow the systematic uptake of WANO-type practices (Liu et al. 2023).

South Korea’s constraints are primarily institutional credibility and stability. Scandals in quality assurance and procurement have weakened confidence in documentation and compliance systems, which directly undermines “equivalence” claims in regional mutual recognition (Andrews-Speed, 2020). Moreover, debates over the internal consistency of quantitative safety goals suggest that even “advanced” formal standards may not translate into harmonized baselines unless definitions and governance roles are aligned (Kim & Kim 2019).

China benefits from strong state coordination, but harmonization is limited by selective integration logic shaped by sovereignty and strategic considerations. Political drivers encourage “international alignment with national control,” which can accelerate capacity building while limiting mutual recognition, where transparency and peer-to-peer interoperability are treated as secondary objectives (Zhao 2022).

V.2 Technical constraints

Technical harmonization is hindered by portability gaps: operating experience travels poorly when reactor generations, digital architectures, and risk-goal formulations diverge, raising the cost of translating “lessons learned” into reusable regional knowledge. In the three-level

metric, technical constraints primarily bind Level 2 (interface alignment) and Level 3 (selective embedding), because heterogeneity in reactor generations, digital I&C architectures, and aging/FOAK challenges increases translation loss at the interface layer and raises the cost of embedding shared learning into plant-specific baselines.

Japan's technology-specific legacies and the ongoing reconfiguration of long-term operation rules reduce the stability of reference baselines, making cross-national standard mapping slower and more contested (Murakami 2024). South Korea illustrates a dual constraint: while risk goals appear stringent, inconsistencies in quantitative goal systems can weaken comparability, and prior data integrity shocks reduce external confidence in technical documentation, both of which impede deeper technical mutual recognition (Kim 2019; Andrews-Speed 2020).

China's modernization pathway—technology transfer combined with indigenous innovation—can widen cross-generation heterogeneity with neighbors, meaning that harmonization must rely on technology-neutral abstraction (risk types, failure modes, and organizational countermeasures) rather than direct rules or component equivalence.

V.3 Political and societal constraints

Regional harmonization is ultimately bounded by trust and policy continuity: without stable societal legitimacy and predictable policy signals, institutional and technical alignment cannot be sustained. In the three-level metric, political and societal constraints primarily bind Level 2 (interface alignment) by narrowing cross-border exchange channels and eroding trust, thereby preventing progression from taxonomy convergence to selective embedding.

Japan's key constraint is the long shadow of Fukushima: public trust and litigation risks increase the political cost of deeper interoperability, incentivizing domestically oriented legitimacy management over regional standard convergence (Normile 2011; Liu et al. 2023). South Korea's legitimacy shocks from scandals politicized oversight and weakened reputational capital, which reduced partners' willingness to rely on Korea as a reference case for mutual recognition (Andrews-Speed 2020).

China's constraint is strategic caution: standard uptake is filtered through sovereignty and security preferences, meaning that convergence is most feasible in low-politics formats (technical exchanges, platform-based learning, shared taxonomies) rather than binding rule convergence (Zhao 2022; IAEA 2025).

V.4 Commonalities and Differences in OE and SAT Adoption in Japan, China, and South Korea

Building on the country case analyses above, this section conducts a cross-national comparison along two axes: (i) the institutional and cooperation logics of operating experience systems; and (ii) the institutional foundations and implementation modes of the systematic

approach to training (SAT). The comparison shows that Japan, China, and South Korea have broadly internalized the WANO/IAEA vocabulary and key operational tools; however, they diverge in terms of who leads organizational learning, how information flows across institutions, and how OE is converted into training and stabilized as organizational capability. These divergences define both the practical constraints and the actionable entry points for the regional harmonization of “best-practice-based” safety baselines.

(1) OE: Divergent institutional logics and cooperation logics

From an institutional-logic perspective, the U.S. OE system is centered on a clearinghouse-style platform that links technical research, licensing, and field inspection within a single information cycle, allowing the operating experience to be translated into review criteria, inspection procedures, and, where necessary, regulatory updates. In contrast, the three East Asian systems reflect different balances between state-led steering and industry self-regulation (Table 3).

Table 3. Comparison of OE mechanisms: Japan-China-South Korea with the United States as a benchmark

Country	Institutional logic	Cooperation logic
Japan	Self-regulation + peer pressure via industry platform(s); strong internal benchmarking, relatively weaker external transparency.	Mainly WANO/IAEA-facing; cross-border engagement is more assessment-driven than network-embedded.
United States	Clearinghouse-centered closed loop linking research–licensing–inspection; OE rapidly translates into guidance/criteria and, when needed, rule updates.	Deeply embedded in multilateral networks; stable regulator–industry trust supports sharing.
China	Regulator-led centralized loop; high consistency, constrained operator autonomy.	Government-coordinated multilateral links plus operator-to-operator channels to import experience.
South Korea	Tripartite collaborative loop with traceable workflows ; balances control and execution.	Bilateral and multilateral cooperation; structured technical exchange and capacity-building strengthens OE depth.

Japan’s OE system is characterized by voluntary self-regulation and peer oversight, in which an industry platform promotes mutual evaluation and benchmarking to pursue excellence across utilities. The strength of this arrangement lies in generating continuous improvement incentives through peer pressure and shared values. However, when improvement cycles are predominantly internalized, limits in public-facing transparency and explainability may reduce societal visibility regarding safety enhancement.

China has developed a regulator-led, centralized, closed-loop OE system that integrates mandatory reporting, staged feedback, and analytical instruments (e.g., PSA/FTA) into a unified process. This model is advantageous for maintaining nationwide consistency and controllability under rapid expansion; however, it also raises a structural tension: how to preserve operator-

driven learning space at the plant level so that OE functions not only as a compliance output but also as an endogenous driver of organizational learning.

South Korea exhibits a tripartite collaborative model in which the regulator, technical support body, and operator are linked through traceable, systematized workflows. By utilizing a national corrective-action tracking system (e.g., CATS), event reporting, corrective actions, investigations, and effectiveness reviews are integrated into a coherent cycle, allowing traceability and transparency at the national level. Compared with Japan’s more self-regulatory orientation and China’s more centralized orientation, Korea represents a comparatively balanced configuration between state steering and operator execution.

From the cooperation-logic perspective, the U.S. benefits from a relatively stable regulator–industry trust relationship and is deeply embedded in multilateral knowledge-sharing networks (e.g., WANO, IAEA, OECD/NEA). Japan relies more heavily on domestic peer mechanisms and, internationally, on assessments and recommendations from the WANO/IAEA. China coordinates international engagement largely through government-led channels while importing experience via operator-to-operator cooperation with foreign counterparts. In addition to multilateral channels, South Korea leverages bilateral cooperation frameworks (e.g., USNRC–KAERI) for technical exchange, human capacity building, and OE-related information sharing (Table 3). Overall, the key differentiators are the openness of cooperation networks, the degree of external transparency, and the routinized capacity for cross-institution coordination.

(2) SAT: Different institutional foundations and implementation modes

Regarding SAT foundations, the U.S. model institutionalizes job/task analysis, instructional design, implementation, and evaluation in a standardized, tool-driven way, and couples training with simulator practice, OJT evaluation, and performance management—thereby making SAT part of the industry’s routine operations. East Asian cases adopt SAT principles to

Table 4. Systematic Approach to Training (SAT): foundations and implementation

Country	Foundation	Implementation
Japan	SAT principles combined with TPT, safety-culture diagnostics, fire drills, and continuous monitoring.	Field-oriented “train–assess–retrain”; OE lessons are progressively fed into frontline behaviors and team performance.
United States	Mature SAT architecture, tool-based and industry-standardized.	Strong coupling with simulators and OJT evaluation; sustained “training–evaluation–improvement” cycle at industry scale.
China	SAT adoption within tiered licensing/qualification and large simulator infrastructure; emphasis on coverage and standardization.	Large-scale, multi-scenario drills; ongoing effort to stabilize the linkage from training outputs to organizational performance routines.
South Korea	SAT/ADDIE widely applied with task analysis and JTA; emphasis on measurability, auditability, and compliance.	Curriculum design tightly coupled with OJT evaluation; standardized, practice-oriented system, with expansion into specialized fields.

varying degrees, but their internalization pathways differ markedly (Table 4).

Japan emphasizes gradual internalization, oriented toward field performance and cultural deepening. Tools such as team performance training (TPT), safety culture diagnostics, fire drills, and continuous monitoring sustain a “training–assessment–retraining” cycle and feed OE lessons into frontline competence development. This approach is highly practice-oriented; however, its systematization and transferability often depend on the intensity and continuity of peer-based evaluation and support.

China adopts SAT methods within a large-scale, tiered qualification system and an extensive simulator-based training infrastructure, with a strong emphasis on coverage and standardization. The key challenge is to further strengthen the coupling between training outputs, organizational management processes, and measurable performance improvements so that the system reliably converts training into verifiable organizational capability rather than remaining primarily procedural and large-scale.

South Korea frequently operationalizes SAT through ADDIE and job/task analysis (JTA), emphasizing measurable objectives and a strong association with OJT evaluation. Its strength lies in standardization and auditability, while an important task is to deepen linkages between training and OE trend analytics, design improvements, and cross-domain organizational learning to enhance diffusion across fields and plant types.

Taken together (Table 4), the U.S. remains ahead in maturity and flexible application, while Japan, China, and South Korea are at different stages of embedding SAT into national institutional settings and organizational cultures—China and Korea rely more on state-led standardization, and Japan relies more on peer mechanisms and self-regulatory platforms to drive cultural change.

(3) Positioning East Asia in best-practice harmonization

In summary, Japan, China, and South Korea share with the U.S. the establishment of OE workflows and systematic training architectures, and they have already translated parts of “best practices” into routines via simulator training and tiered qualification systems. However, structural differences remain in leadership logic, transparency, degrees of industry self-regulation, and the depth of OE–SAT coupling. For regional harmonization, these differences are both constraints and actionable entry points: prioritizing transferable “mechanism-level” elements—such as event screening/gradation, corrective-action tracking, training triggers, and retraining mechanisms—may allow for incremental convergence without immediately confronting highly politicized domains.

VI. Comparative Analysis of Operational Performance of Major Nuclear Power Units in East Asia

VI.1 Research design and data

VI.1.1 Section purpose and research questions

The previous sections compared Japan, China, and South Korea in terms of WANO best practice adoption and the barriers to standard harmonization across institutional, technical, and political dimensions. However, institutional descriptions alone do not fully capture how these differences translate into observable operational behaviors. Therefore, this section introduces unit-level annual performance data and conducts an illustrative time-series comparison of a limited set of representative reactors. The objective is not to rank national safety performance or make causal claims via econometric identification but to address two questions:

(1) How do major institutional/political shocks (e.g., nationwide shutdowns, regulatory restructuring, local politics, and litigation) leave identifiable “traces” in EAF/FLR trajectories?

(2) In domains such as FOAK introduction and aging management, do the three countries exhibit transferable “shock–correction–recovery” patterns that can inform regional harmonization discussions?

These “shock–correction–recovery” signatures are used as mechanism-tracing evidence rather than as a performance ranking: they indicate where learning breaks down or stabilizes in practice. In terms of the three-level metric defined in Sect. 2.3, the section treats event-year signatures as inputs for Level 1 (taxonomy convergence) and Level 2 (interface alignment), while using the discussion in Sect. 6.5 to clarify what would be required for Level 3 (selective embedding) to become observable.

VI.1.2 Data source and case selection

The dataset is drawn primarily from the IAEA’s annual Operating Experience with Nuclear Power Stations in Member States reports, which provide unit–year operational indicators (IAEA, 2002–2023). Case selection was based on two principles.

(1) coverage of heterogeneous institutional/technological stages (joint-venture baseline,

Table 5. Selected units and observation windows

Country	Unit	Reactor type / Generation	Observation window
China	DAYA BAY-1	PWR (early imported/JV)	2002–2023
China	QINSHAN 2-1	PWR (indigenized Gen-II)	2002–2023
China	SANMEN-1	AP1000 (Gen-III/FOAK)	2018–2023
Japan	SENDAI-1	PWR	2002–2023
Japan	OHI-3	PWR	2002–2023
ROK	HANBIT-3	PWR (standardized unit)	2002–2023
ROK	WOLSONG-3	PHWR/CANDU (ageing unit)	2002–2023
ROK	SAEUL-1	APR1400 (Gen-III)	2017–2023

indigenization “learning” phase, FOAK/Gen-III demonstration, pre/post-Fukushima discontinuity, standardized governance with FOAK, and aging cases);

(2) sufficiently long observation windows to examine “shock → adjustment → convergence” paths.

The selected units and their rationales are summarized in Table 6, while the full time-series tables and line charts are provided in Appendix A.

VI.1.3 Indicators and analytical procedure

To maximize interpretability and align with the institutional discussion, the analysis focuses on two indicators: EAF⁵ (Energy Availability Factor); FLR⁶ (Forced Loss Rate).

The procedure is:

(1) visualize unit-level annual EAF/FLR time series and annotate key institutional/technical milestones;

(2) compare patterns within each country (stable periods, volatility, convergence);

(3) compare cross-country “shock archetypes” (policy-driven shutdown, event-year concentrated correction, convergence/learning curve) and discuss implications for OE mechanisms and training system (SAT) coupling in regional harmonization.

VI.1.4 Scope and limitations

The small number of cases means that the results should be interpreted as pattern evidence rather than national averages. The focus on EAF/FLR does not cover outcome-oriented safety variables (e.g., event severity, releases, and occupational doses). Reactor type, vintage, and grid context may shape performance curves; therefore, this section prioritizes governance-level interpretation over full technical control. Accordingly, this section aims to corroborate and sharpen the institutional narrative, rather than claiming definitive causality.

VI.2 China: expansion with institutional consolidation

China’s three cases represent distinct stages: an early joint-venture unit (DAYA BAY-1), an indigenized Gen-II unit (QINSHAN 2-1), and a Gen-III FOAK demonstration unit (SANMEN-1). As shown in Appendix A, DAYA BAY-1 maintains persistently high EAF and near-zero FLR in most years, functioning as a “stability baseline” under mature technology and comparatively standardized management routines.

QINSHAN 2-1 displays a different early-life trajectory. The time series contains “event years” with visibly lower EAF and elevated FLR during the early 2000s, followed by a pronounced convergence toward a high EAF and low FLR thereafter. Interpreted through the institutional lens developed in Section 4, this pattern is consistent with a learning-and-stabilization process in which early design/implementation frictions were progressively absorbed through corrective

modifications, procedural refinement, and strengthened training feedback loops.

SANMEN-1, a Gen-III FOAK unit, shows high overall availability after commercial operation, but with several years in which the FLR rises and the EAF dips relative to its baseline value. Notably, the deviations appear concentrated rather than persistent, suggesting a governance style that addresses FOAK-specific issues through discrete outage windows and engineering fixes without destabilizing the longer-run availability trend. From the perspective of regional standardization, China's cases imply that "transferable experience" is most feasible when lessons from FOAK introduction are abstracted into problem types (e.g., equipment qualification, commissioning-to-operation interfaces) rather than treated as unit-specific anecdotes.

VI.3 Japan: policy-driven discontinuity and differentiated recovery

Japan's unit-level patterns are dominated by a clear structural break after the Fukushima Daiichi nuclear accident. For SENDAI-1 and OHI-3, the post-2011 period includes multi-year observations in which EAF drops to zero, whereas FLR also remains near zero, indicating prolonged shutdowns driven primarily by policy and regulatory processes rather than equipment failures. This "non-technical shutdown signature" provides a concrete illustration of Section 5's claim that political-social constraints can dominate operational outcomes even when technical capacity remains intact.

The post-restart trajectories diverged. SENDAI-1 returns relatively quickly to a high-availability regime with low forced losses, resembling a "faster stabilization" pathway under a revised regulatory framework. OHI-3, by contrast, exhibits a more volatile recovery, with larger swings in the EAF and occasional increases in forced losses. Consistent with the discussion in Section 4, the divergence suggests that local political conditions and litigation dynamics can interact with plant-level maintenance cycles and aging-management requirements, producing prolonged uncertainty that is legible in the year-by-year operating record.

VI.4 Republic of Korea: routine stability with concentrated "event years"

ROK's patterns reflect centralized operations and high standardization. Across HANBIT-3 and, for much of the period, WOLSONG-3, the time series shows long stretches of high EAF and very low FLR, consistent with a "routine stability" regime under a unified operator and tightly coupled technical support. Importantly, when major issues surface, they appear as sharply concentrated "event years," in which EAF drops and FLR spikes, followed by a return to a high-stability regime. This pattern is visible in HANBIT-3 and is even more pronounced for WOLSONG-3 when aging-related concerns become salient.

SAEUL-1, a Gen-III unit, displays a typical new-build signature: high early performance punctuated by a subsequent dip and recovery, suggesting that initial post-COD issues were addressed through discrete corrective windows, supported by standardized operating experience processing and training updates. From the viewpoint of harmonization, the ROK's cases highlight

“event-year governance” as a salient institutional style: major issues are managed through concentrated outages and systematic corrective action tracking rather than incremental degradation across many years.

VI.5 Integrated discussion: what operating data add to the standardization debate

Taken together, the selected cases suggest a shared baseline—most “normal years” in all three countries achieve high availability with low forced losses—while revealing divergent governance signatures under stress in the bad years. Japan illustrates a policy-driven discontinuity (multi-year EAF=0 with low FLR) and a differentiated recovery shaped by local political constraints. China illustrates learning-driven convergence, in which early life or FOAK issues are compressed into a limited number of identifiable deviation years, followed by stabilization. ROK illustrates routine stability with concentrated event-year corrections, where large deviations are episodic and followed by relatively rapid re-stabilization.

Interpreted through the partial-harmonization metric (Sect. 2.3), these signatures suggest that East Asia already has a practical basis for Level 1 convergence—shared labels and recurring “event-year” problem types—while cross-country portability weakens when the learning interfaces diverge (Level 2). The implication is that the realistic target is not identical codes but compatible decision gates: common triggers for shutdown/diagnosis, minimum information sets, and standardized feedback products that reduce translation loss. Deeper Level 3 embedding would then be evidenced not by smoother curves per se, but by whether shared event types are systematically referenced in domestic risk reviews, corrective-action programs, and OE-to-SAT updates.

These patterns matter for regional standardization because they point to realistic “low-politics” entry points. Rather than seeking uniformity in national licensing or energy politics, regional efforts could prioritize (i) shared typologies for “event years” (trigger conditions, minimum information sets, outage decision principles), and (ii) modularized OE-to-training translation templates that allow lessons from new builds and aging management to be mapped onto different fleet contexts. In this sense, operating data serve as a pragmatic bridge between institutional narratives (Sections 4 and 5) and actionable policy design (Section 7): they indicate where convergence already exists (routine performance) and where harmonization must focus (shock handling and lesson institutionalization).

VII. Conclusions

This chapter examined how WANO-related best practices are adopted and institutionalized through operating experience feedback and a systematic approach to training, why harmonization remains difficult among Japan, China, and the Republic of Korea, and what form of convergence is feasible under real-world political, institutional, and technological constraints. Rather than assessing harmonization as the unification of national rules, the analysis reframed it as the compatibility of learning and decision-making interfaces that translate experience into routine

safety practices.

VII.1 Core Findings

Four core findings emerge. First, despite the widespread adoption of common WANO and IAEA terminology, the three countries operate under structurally distinct governance constraints. Japan’s post-Fukushima system is shaped by policy-driven discontinuity and restart uncertainty; China faces coordination challenges associated with rapid expansion and first-of-a-kind (FOAK) deployment; and the ROK continues to balance regulatory independence with corporate governance and supply-chain integrity. These differences condition how best practices are interpreted and embedded.

Second, the principal obstacle to harmonization lies not in the absence of OE or SAT mechanisms, but in the misalignment of decision gates—when shutdowns are triggered, how evidence thresholds are defined, how corrective actions are authorized, and how recovery is justified (e.g., screening triggers, analytic handoffs, and feedback-product formats). Convergence therefore depends less on identical codes than on interoperable interfaces that structure learning and decision-making.

Third, institutional differences leave observable traces in operating performance. The descriptive EAF/FLR time-series analysis reveals distinct “shock–recovery” or “event-year” patterns: policy-induced discontinuities in Japan, FOAK- or early-life-related debugging windows in China, and concentrated corrective or aging-related outages in the ROK. These patterns illustrate how governance arrangements shape operational responses and help contextualize mechanism–performance linkages, rather than serving as performance rankings.

Fourth, feasible convergence is most likely in domains characterized by high technical salience and relatively low political sensitivity. These include FOAK early-life operating issues, aging-management triggers and lifetime decision gates, recurring human-performance patterns, and common-cause failure logic—areas where shared learning yields tangible risk-reduction benefits without directly challenging national sovereignty.

VII.2 Policy Implications: A Staged Pathway to Partial Harmonization

Building on these findings, the study proposes a staged approach to regional cooperation grounded in “portable learning interfaces.” At the first stage, harmonization should focus on taxonomy convergence: translating plant-specific events into standardized “experience types” that can be shared across borders. At the second stage, attention should shift to interface alignment by standardizing learning gates—screening criteria, analytic handoffs, and feedback products—within OE and SAT systems. Only at the third stage should selective embedding be pursued, whereby aligned interfaces are routinized through domestic risk reviews, corrective-action programs, and SAT-based training cycles.

Operationally, this implies prioritizing low-politics cooperation instruments: a regional

OE case library curated around technically salient but politically manageable event types; modular SAT-based co-training packages for FOAK and aging-related challenges; and standing technical working groups that produce guidance rather than binding rules. Such measures allow cooperation to accumulate incrementally, making convergence assessable and implementable rather than rhetorical.

VII.3 Limitations and Directions for future research

The study has several limitations. The performance analysis relies on a limited set of publicly available indicators and does not support causal inference or statistical ranking. Social and political actors beyond regulators and operators are addressed selectively, despite their importance in shaping safety outcomes. Finally, the proposed cooperation pathways have not been stress-tested against administrative burden or political cost. Future research should expand performance indicators, incorporate expert interviews and stakeholder analysis, and use scenario-based methods to evaluate the robustness of alternative cooperation designs.

VII.4 Final Conclusion

Under the realistic constraints facing East Asia, nuclear safety harmonization is best pursued as an incremental convergence of learning interfaces rather than as a rapid regulatory unification of rules. By converting operational volatility into portable experience types, aligning decision gates for event-year management, and embedding OE-to-SAT pathways that demonstrably influence risk reviews and training updates, Japan, China, and the ROK can achieve a pragmatic form of regional compatibility—one that builds trust through low-politics cooperation and delivers measurable risk-reduction benefits over time.

Note

- 1) The initial scoping of U.S. “best practice” materials was supported by keyword searches in the NRC ADAMS database (e.g., “best practice”); one reference point is an NRC best-practice certification report (ADAMS Accession No. ML23054A245).
- 2) Based on the *NRC OE PROGRAMS 2015*
- 3) Based on the *NRC OE PROGRAMS 2015*
- 4) Based on the *White Paper on Nuclear Safety in China*
- 5) capturing overall annual availability (including planned and unplanned outages)
- 6) capturing the intensity and concentration of unplanned losses (“event years”).

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Appendix A

Appendix A compiles the time-series tables and figures of annual operating indicators—Energy Availability Factor (EAF) and Forced Loss Rate (FLR)—for the representative reactor units analyzed in Chapter 6. The data are compiled from IAEA, *Operating Experience with Nuclear Power Stations in Member States* (2024 edition), which draws on the IAEA Power Reactor Information System (PRIS) and reports annual operating-performance indicators up to 2023.

EAF and FLR are adopted in this study because they are consistently reported across units and countries and capture complementary aspects of operating performance relevant to routine

reliability and outage behavior. In general terms, EAF indicates the extent to which a unit is available to generate electricity over a year, while FLR reflects performance loss associated with forced (unplanned) outages; read together, they provide a transparent descriptive window into year-by-year operating stability and disruption–recovery patterns discussed in the main text.

Fig.4 The full time-series tables and line charts of units

