

A Traceable Integrated Assessment Framework for Achievable Target Set Determination

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***Keywords :** achievable target set, physical protection, radiological sabotage, 10 CFR 73.100, traceability

1. Introduction

Target Set identification, vital area analysis, and physical protection system (PPS) evaluation are established activities for protection against radiological sabotage, but they are normally performed with different models and decision criteria. A Target Set is a combination of structures, systems, components, or operator actions whose loss can lead to unacceptable consequences. An Achievable Target Set (ATS) additionally requires that a design-basis threat (DBT) adversary can defeat the complete combination and that the resulting consequence cannot be mitigated or reversed. Treating every Target Set as achievable can overstate vulnerability, whereas evaluating accessibility or PPS performance alone can understate the consequence conditions required for an ATS.

The technology-inclusive requirements in 10 CFR 73.100 make this determination central. The existing 10 CFR 73.55 aims to prevent significant core damage and spent fuel sabotage and combines performance criteria with prescriptive requirements for personnel, barriers, and access control [1]. In contrast, 10 CFR 73.100 sets the protection outcome as preventing a release from any radionuclide source that exceeds the dose reference values in 10 CFR 53.210, and it grades the applicable requirements according to whether an ATS exists and whether active measures are credited to demonstrate its absence [2,3]. Regulatory Guide (RG) 5.97 describes acceptable methods for meeting the performance requirements, such as intrusion detection and assessment, security communication and response, and vehicle bomb protection [4]. Because the ATS result determines the scope of the protection program, the determination itself needs a traceable basis.

However, the detailed implementation procedures of the latest RG 5.81 revision [5] and facility-specific ATS analyses are not publicly available, and actual DBT details and protection performance data are also non-public. The public RG 5.81 Rev. 1 provides Target Set identification steps, but it was framed around significant core damage and spent fuel sabotage rather than the 10 CFR 53.210 dose outcome [6]. A public research method must therefore operationalize only the disclosed regulatory conditions without reconstructing sensitive procedures or assuming unavailable facility data.

This paper proposes a traceable integrated assessment framework that takes an identified Target Set as input

and evaluates ATS status under a common plant state, attack scenario, damage state, and time axis. The contributions are: (1) a single framework that combines the three regulatory conditions as gates evaluated on one scenario; (2) an upstream trace from the radiological consequence to Target Set elements and a downstream mapping to the regulatory branches of 10 CFR 73.100(a)(1); (3) a requirement-to-evidence record that prevents unsupported Non-ATS decisions; and (4) an illustrative small loss-of-coolant accident (SLOCA) case and a validation design. The study does not create new Target Sets or determine an official ATS or vital area for an actual facility; locations, times, protection values, and attack capabilities are represented by virtual, normalized, or interval data, and attack actions are modeled only at the functional-loss-effect level.

2. Regulatory Basis

2.1 Three cumulative ATS conditions

Under 10 CFR 73.100(b)(5), the licensee must further identify ATSS through a site-specific analysis, and a Target Set is an ATS only when it satisfies all three conditions in Table I [2]. If any condition is not met, the Target Set is not an ATS. In this study, each condition is evaluated by a corresponding gate.

Table I: ATS conditions and corresponding gates

Condition	Regulatory condition	Gate
C1 DBT achievability	Within DBT capabilities to compromise, destroy, or render the Target Set non-functional	G1 attack feasibility
C2 Inability to mitigate	Cannot be mitigated after adversary interference is precluded and before a release exceeding the 10 CFR 53.210 values	G2 post-interference mitigation failure
C3 Irreversible exceedance	If defeated, results irreversibly in exceedance of the 10 CFR 53.210 dose reference values	G3 irreversible radiological consequence

2.2 Active-measure credit and regulatory branches

Because 10 CFR 73.100 distinguishes whether ATS absence depends on active measures, the same Target Set is assessed under two credit cases [2]. P0 does not credit successful operator action, active mitigation, detection,

assessment, or armed response; passive or inherent features and intrinsic limits of the abstracted DBT condition remain applicable. P1 credits only active measures supported by test or analysis, equipment availability, procedures, training, supporting-system availability, and documented failure modes. The plant-level outcome determines the branch in 10 CFR 73.100(a)(1), as shown in Table II.

3. Integrated Assessment Framework

3.1 Framework structure and decision rule

In the framework, four inputs, namely the identified Target Set with its upstream trace, the plant state, the DBT scenario set, and the credit case, define a common Case ID. Within this Case ID, G1, G2, and G3 are evaluated on the same scenario, damage state, time axis, and evidence: G1 passes the common damage state to G2, and G2 passes the residual plant state to G3. Let the j -th Target Set be $S_j = \{e_1, e_2, \dots, e_n\}$. For plant state z , credit case c , and DBT-bounded scenario π , the decision rule is

$$ATS(S_j, z, c) = 1 \Leftrightarrow \exists \pi \in \Pi_{DBT}(S_j, z): G1 \wedge G2 \wedge G3(1)$$

Favorable results from different routes, damage states, or timing assumptions are not combined, because separate optimization of the gates could create an artificial ATS that no single adversary scenario can produce. Each gate returns PASS, FAIL, or Undetermined. A Target Set is an ATS when at least one scenario passes G1–G3, and Non-ATS only when every credible scenario in the defined envelope has sufficient evidence to fail at least one gate. Missing critical evidence, unresolved model scope, or an untested scenario yields Indeterminate rather than Non-ATS. A plant-level absence claim requires every Target Set in the envelope to be Non-ATS under the corresponding credit case; an individual Non-ATS or Indeterminate result cannot be promoted to such a claim.

Table II: Outcome-to-branch mapping under 10 CFR 73.100(a)(1)

Plant-level outcome	Branch	Consequence
No ATS under P0	(a)(1)(i)	Exempt from the remaining requirements of 10 CFR 73.100
No ATS only under P1	(a)(1)(ii)	Credited active measures must be ensured against threats up to the DBT through the protection program
ATS exists or absence not demonstrated	(a)(1)(iii)	10 CFR 73.100 requirements apply, including physical security, training and qualification, safeguards contingency, and cyber security plans

3.2 Upstream Target Set trace

The framework does not generate Target Sets, but it records how the input Target Set was derived so that each decision can be traced to its radiological basis. RG 5.81 Rev. 1 organizes the work into analysis-team formation, Target Set objective determination, element identification, Target Set generation, and achievable Target Set screening [6]. As shown in Fig. 1, STEP 3 supplies the elements whose functional losses are assessed, and STEP 5 corresponds to the achievable Target Set screening addressed by the proposed framework.



Fig. 1. Target Set identification procedure based on RG 5.81 Rev. 1 and its link to the proposed framework.

Element identification is recorded in two sub-steps (Fig. 2). First, probabilistic risk assessment (PRA) event trees start from a consequence that can exceed the 10 CFR 53.210 values, select initiating events such as SLOCA, loss of offsite power, loss of feedwater, and transients, including maliciously induced ones, and identify the required safety functions and success criteria; in Fig. 2(a), the APR1400 SLOCA event tree [7] develops nine sequences through reactor trip (RT), safety injection (SIS), secondary heat removal (SHR), aggressive secondary cooling (ASC), shutdown cooling system injection (SCSI), safety depressurization (BLEED), and containment heat removal (LHR); six sequences end in core damage, and the failed SCSI and LHR branches (sequences 03, 06, and 07) identify long-term heat removal by the residual heat removal (RHR) function as a required function. Second, fault trees expand each required function into frontline-system failure, support-system loss such as AC/DC power or cooling water, operator-action failure, and digital or control-function loss (Fig. 2(b)); for RHR, the top event G-RHR-TOP is developed through OR gates into the

failures of RHR trains A and B, common support-function loss (power, service water cooling, and I&C), and operator-action failure, and the support-function gates are further developed into service water and I&C events. The resulting basic events (e.g., P-RHRA, AC-FAIL, SW-PUMP, I&C-SIG) become Target Set element candidates together with their dependencies and common-cause effects.

Elements are normalized as analysis objects that include the required functional-loss state and minimum loss duration rather than component names only. If dependency analysis reveals a functional-loss combination absent from the input analysis, it is returned to the identification stage instead of being declared an ATS, so that the ATS procedure is not used to generate new Target Sets.

3.3 Case ID, traceability, and evidence

ATS results are conditional on the Target Set version, plant state, DBT assumptions, scenario, damage state, and credit case, which together form the Case ID. A decision record links the applicable requirement, decision question, upstream trace, input and model versions, assumptions, Evidence ID, intermediate results, gate result, final decision, regulatory branch, and change trigger. This enables reverse tracing from the decision to the supporting regulatory condition and prevents silent changes in scenario context between modules. Evidence is graded for research control from measured or tested data, validated analysis, engineering calculation or analogous public information, and structured expert judgment, to unsupported assumptions or missing data; the grades are not regulatory classifications. When a decision depends on unsupported or missing evidence, the gate is marked Undetermined, so data scarcity cannot serve as evidence of ATS absence.

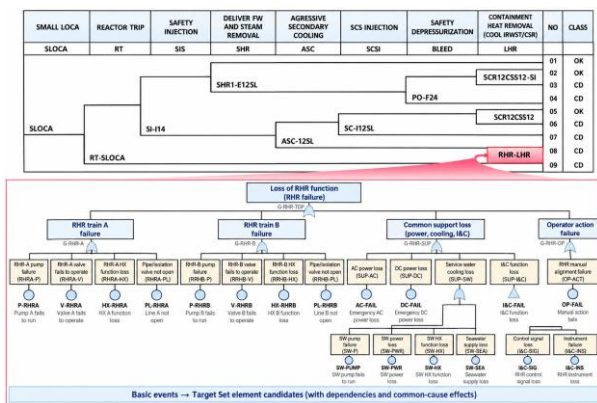


Fig. 2. Identification of Target Set elements: (a) APR1400 SLOCA event tree reconstructed from the publicly available design control document [7], identifying the required safety functions and (b) fault tree for loss of residual heat removal (RHR).

3.4 G1: DBT attack feasibility

G1 is reviewed against the DBT categories in 10 CFR 73.1(a)(1), with the external-adversary attributes further divided as in Table III [8]. The categories are not independent success conditions; they bound the resources and effects that one scenario may combine.

Table III: DBT categories and G1 analysis focus

Category (clause)	G1 analysis focus
External assault (i)	External capability and access conditions required for Target Set functional loss
Training, knowledge (i)(A)	Knowledge and skill needed to identify elements and produce the losses
Inside assistance (i)(B)	Effect on access, information, and achievement of functional loss
Weapons (i)(C)	Physical effects required for loss and consistency with DBT weapons
Hand-carried equipment (i)(D)	Means to disable equipment, structures, and support functions
Transport (i)(E)	Applicability given site location and access conditions
Internal threat (ii)	Functional loss achievable by an insider
Land vehicle bomb (iii)	Relation of site and structural features to Target Set functions
Waterborne vehicle bomb (iv)	Water access and functional effects on related structures
Cyber attack (v)	Whether digital compromise causes Target Set or support-function loss

The facility and scenario are represented as linked functional, spatial, dependency, attack-task, protection, mitigation, and consequence layers. IAEA NSS No. 48-T provides the basis for facility-to-area transformation and spatial interaction, although it does not define the U.S. ATS decision [9]. A directed acyclic attack-task graph models movement, boundary transition, target identification, preparation, functional loss, and transition between targets under precedence and resource constraints; parallel completion time is the latest branch plus synchronization time. G1 passes only when valid paths reach all required elements, the effects remain within the abstracted DBT capability, and the element losses overlap for at least the required duration. PPS timeliness is evaluated at each detection opportunity by comparing assessment, communication, deployment, and interdiction time with the remaining attack-task makespan, following the detection-delay-response and critical detection point concepts in IAEA NSS No. 40-T [10]. No universal probability threshold is assumed to remove a Target Set from consideration.

For the cyber category, the cyber-enabled accident scenario (CEAS) and cyber-enabled intrusion scenario (CEIS) concepts in RG 5.96 for 10 CFR 73.110 provide compatible inputs [11]. In a preliminary application to the publicly available APR1400 SLOCA event tree [7], six of nine end states lead to core damage, and each was converted into a candidate CEAS by assuming compromise of digital functions supporting the failed top events, such as auxiliary feedwater actuation or the

information and operation needed to open the pilot-operated safety relief valves. Such scenarios supply digitally induced functional losses to G1, but because Level 1 PRA ends at core damage, they do not by themselves establish G3.

3.5 G2: post-interference mitigation

Let t_{clear} be the time at which adversary interference is removed and t_{exceed} the latest time before a release leading to the 10 CFR 53.210 threshold becomes unavoidable without further mitigation. The mitigation window is

$$\Delta T_{mit} = t_{exceed} - t_{clear} \quad (2)$$

A candidate action takes effect at t_{eff} and is credible only if $t_{eff} \leq t_{exceed}$ (Fig. 3). The review covers mitigation means (remaining safety functions, alternate systems, isolation, injection, heat removal, and release reduction), time (recognition, preparation, movement, operation, and onset of effect), availability (power, cooling water, air, instrumentation, access routes, environment, personnel, and equipment), and operator-action conditions (approved procedures, staged equipment, maintained training, accessibility, and security delay). Personnel and equipment cannot be double-booked, and the consequence module is rerun after each candidate action. If one credible action prevents exceedance, G2 fails; the mere existence of a procedure or a nominally short recovery time is insufficient. G2 thus asks whether the release can be prevented before t_{exceed} , not whether the plant can eventually be recovered.

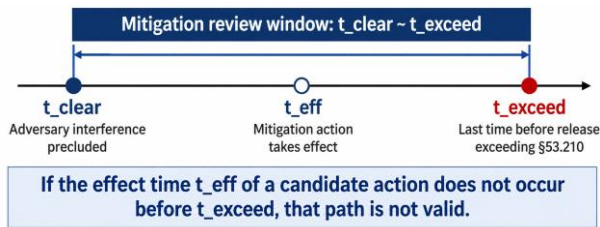


Fig. 3. Mitigation review window between the interference-clearance time and the exceedance limit time, and the G2 (C2) review criteria.

3.6 G3: irreversible radiological consequence

Table IV: Dose reference values in 10 CFR 53.210

Item	Exclusion area boundary (EAB)	Low population zone (LPZ)
Reference value	25 rem (250 mSv) TEDE	25 rem (250 mSv) TEDE
Exposure period	Any two-hour period after release onset	Entire passage of the radioactive plume
Evaluation	Conservative assumptions and site-specific conditions reflected	Conservative assumptions and site-specific conditions reflected

Table V: Irreversibility review items for G3 (C3)

Review item	Content and meaning
Initial state	Applicable operating mode and Target Set loss time
Lost functions	Safety and support functions removed by defeat
Remaining functions	Surviving functions such as passive safety, isolation, barriers, and alternate systems
Accident progression	Progression path from functional loss to nuclide release
Source term	Nuclides, release amount, release onset, and duration
Dose analysis	TEDE at the EAB and LPZ
Irreversibility	Whether remaining functions and operator actions can avert exceedance
Uncertainty	Models, input data, SSC states, and conservative assumptions

The consequence module maps the common damage state to exceedance time, normalized dose ratio, recovery state, and irreversibility. Consistent with 10 CFR 53.210, the dose ratio is the maximum of the exclusion area boundary (EAB) dose for any two-hour period after release initiation and the low population zone (LPZ) dose over plume passage, each normalized by 250 mSv (25 rem) total effective dose equivalent (TEDE) [3]. G3 requires a ratio greater than one and evidence that no credible recovery path can return the state below the reference value. Irreversibility does not mean permanent equipment damage; it means that exceedance can no longer be averted after the remaining functions, alternative actions, and mitigation paths are considered. The dose reference values are summarized in Table IV, and the review items for irreversibility in Table V. To make the term computable, a research variable, Point of No Return, is defined as the earliest time after which every credible recovery action still leaves the dose ratio above one; it is not a regulatory term. The interface accepts validated public analyses, simplified state-transition models, or pre-labeled synthetic consequence cases rather than a new plant-specific model.

4. Illustrative Application: SLOCA in a Notional SMR

A notional pressurized-water SMR in normal power operation is considered (Fig. 4). An adversary within the DBT simultaneously defeats the emergency diesel generators (EDGs) in the auxiliary building and the safety I&C in the main control building. With offsite power lost and safety I&C unavailable, core-cooling margin decreases and the accident progresses in a SLOCA sequence. Inputs are a site-specific DBT and scenario review, PRA event trees, source-term and dose calculations, a mitigation-availability review, and walkdown, task-time, staging, and training information.

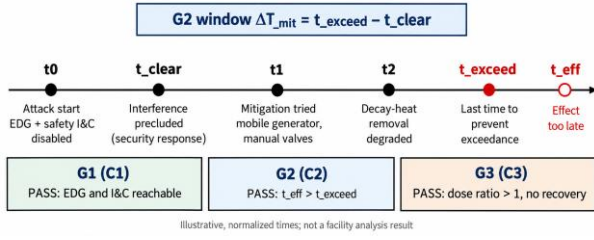


Fig. 4. Illustrative SLOCA timeline and gate results for a notional SMR (normalized times).

For G1, the DBT personnel, weapons, intrusion, and destruction capabilities can reach both elements and produce overlapping loss under the notional structural, access, and protection assumptions. For G2, the mobile generator connection, alternate systems, operator actions, and portable equipment are reviewed after t_{clear} ; because alternate power connection needs more time than the window allows, t_{eff} falls after t_{exceed} . For G3, the EAB two-hour and LPZ plume-passage TEDE exceed 25 rem, and the remaining functions cannot return the state below the reference value. The case is therefore labeled ATS under P0. If a staged generator with a validated connection time yielded $t_{eff} < t_{exceed}$ and its credit were supported, G2 would fail only under P1; if all other Target Sets were also excluded, the plant would fall under branch (a)(1)(ii), with the credited measure retained as a dependency. The case serves as a pre-labeled synthetic case, not a facility result.

5. Regulatory Branching by ATS and Active-Measure Credit

Fig. 5 shows how the result of the site-specific ATS analysis determines the scope of the 10 CFR 73.100 requirements under 10 CFR 73.100(a)(1) [2]. Three considerations govern the branch: whether an ATS exists according to the site-specific analysis; whether active measures, such as training, personnel, equipment, and procedures, are credited to demonstrate ATS absence, which requires their reliability against the DBT to be evaluated; and the resulting scope of the requirements.

If no ATS exists without crediting active measures, the plant is exempt from the remaining requirements of 10 CFR 73.100 under branch (a)(1)(i). If ATS absence depends on credited active measures, the protection program must ensure those measures against threats up to the DBT under branch (a)(1)(ii). If an ATS exists, or its absence is not demonstrated, the 10 CFR 73.100 requirements apply under branch (a)(1)(iii), including the physical security, training and qualification, safeguards contingency, and cyber security plans. In the proposed framework, this branch is reached only through the P0/P1 outcomes of Section 2.2, so an individual Non-ATS or Indeterminate result cannot place a plant in branch (i) or (ii).

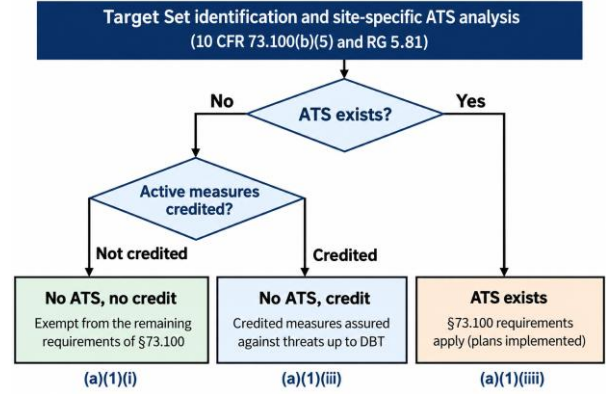


Fig. 5. Regulatory branches according to ATS existence and active-measure credit under 10 CFR 73.100(a)(1).

6. Validation Plan and Expected Contribution

Because actual ATS lists, detailed DBT data, and facility protection performance are not public, the framework cannot be validated against one authoritative answer. First, regulatory traceability review checks whether each public condition is represented and whether decisions can be traced through inputs, models, and evidence. Second, pre-labeled synthetic cases, including the SLOCA case, test known outcomes: no valid path, insufficient resources, unmet simultaneity, successful P1 response, successful mitigation, sub-threshold consequence, recoverable exceedance, complete G1–G3 satisfaction, and missing critical evidence. Third, staged comparison adds dependencies, resource and sequence constraints, PPS timing, mitigation, consequence, irreversibility, and the decision-withholding rule to a baseline of Target Set composition and function-loss logic, while component ablation removes each layer and measures decision changes. Fourth, sensitivity analysis varies task and response times, equipment availability, model error, insider condition, route closure, maintenance state, and common dependencies.

Metrics include requirement coverage, complete trace ratio, synthetic-case accuracy, precision, recall, F2 score, false-negative rate, scenario-context mismatch count, ablation-induced decision change, and the share of uncertainty ranges that preserve the baseline decision; F2 and false-negative rate are emphasized because missing an ATS is more significant than over-screening. Site drawings, access routes, I&C architecture, support-system data, and detailed quantification criteria are not public, so such inputs are represented as intervals or Undetermined values. The results demonstrate logical validity, traceability, and feasibility rather than regulatory accuracy for an actual plant. The expected contribution is a transparent interface among Target Set analysis, spatial reasoning, PPS evaluation, mitigation, consequence assessment, and the resulting regulatory branch.

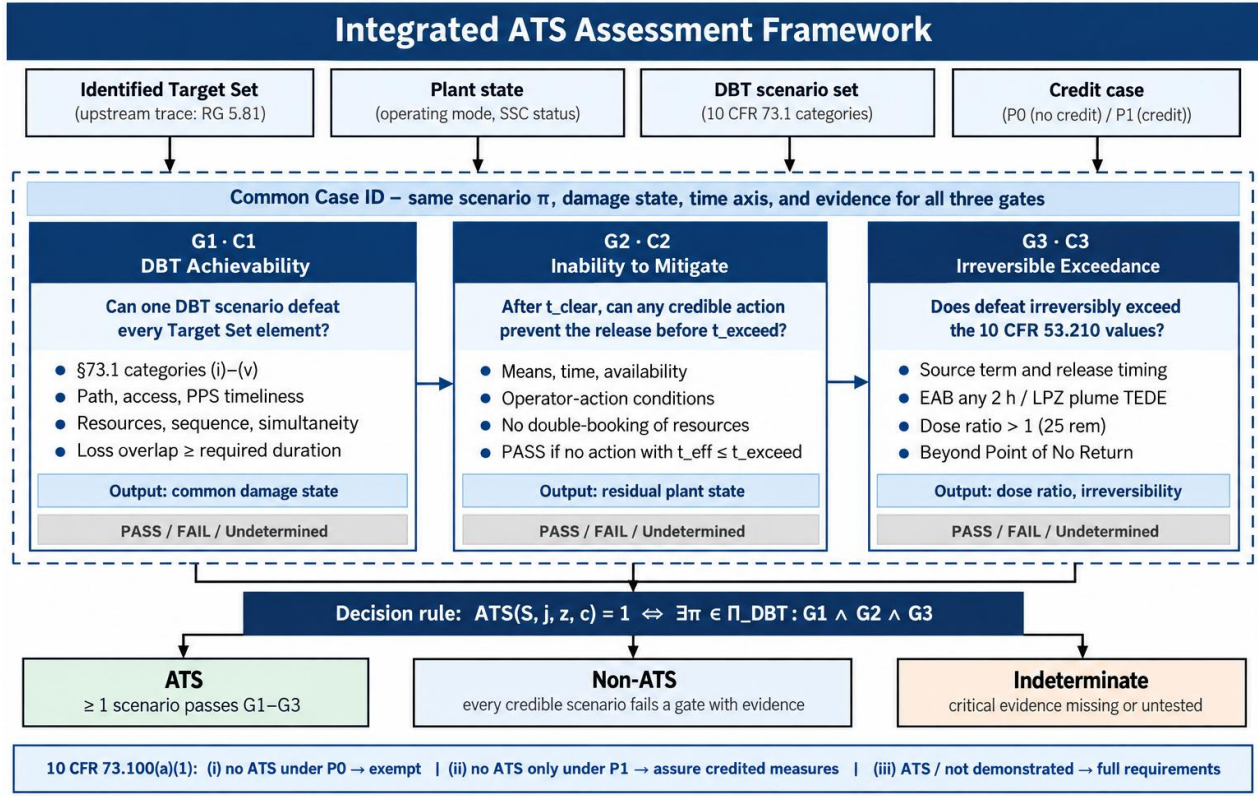


Fig. 6. Integrated ATS assessment framework combining the three conditions (C1–C3) as gates G1–G3 under a common Case ID.

7. Final Integrated Assessment Framework

Fig. 6 integrates the elements of Sections 2–5 into the final assessment framework. It is read from top to bottom in four layers: inputs, gate evaluation within a common Case ID, decision integration, and regulatory mapping with traceability.

The input layer fixes the conditions of a case: the identified Target Set S_j with its upstream trace (Section 3.2), the plant state z including operating mode and SSC status, the DBT scenario set Π_{DBT} bounded by the 10 CFR 73.1 categories (Table III), and the credit case c (P0 or P1). Together with the scenario and damage state, these inputs form the Case ID (Section 3.3). The dashed frame indicates that all three gates are evaluated on the same scenario π , damage state, time axis, and evidence, which enforces the scenario-consistency rule.

Inside the frame, each gate is defined by a decision question, review items, and an output passed to the next gate. G1 asks whether one DBT scenario can defeat every element, reviewing attack path, access, PPS timeliness, resources, sequence, simultaneity, and loss overlap; its output is the common damage state. G2 starts from this damage state and asks whether any credible action can prevent the release between t_{clear} and t_{exceed} , reviewing mitigation means, time, availability, operator-action conditions, and resource double-booking; it passes when no action satisfies $t_{\text{eff}} \leq t_{\text{exceed}}$, and its output is the residual plant state. G3 evaluates the source term, release timing, and EAB and LPZ TEDE for this residual state

and passes when the dose ratio exceeds one beyond the Point of No Return. Each gate returns PASS, FAIL, or Undetermined.

The decision layer combines the gate results through Eq. (1). ATS is assigned when at least one scenario passes all three gates, Non-ATS when every credible scenario fails a gate with sufficient evidence, and Indeterminate when critical evidence is missing or a scenario is untested. The result is then mapped to 10 CFR 73.100(a)(1) as in Table II and Fig. 5: absence under P0 leads to branch (i), absence only under P1 leads to branch (ii) with the credited measures to be assured, and an existing or undemonstrated ATS leads to branch (iii). The traceability record at the bottom of Fig. 6 retains the requirement, question, evidence ID, model version, assumption, gate result, and change trigger for each decision, so that a change in input or evidence identifies the decisions that must be re-evaluated.

Applied to the SLOCA case in Section 4, the EDG and safety I&C losses form the common damage state from G1, the late t_{eff} of the alternate power connection makes G2 PASS, and the exceedance of 25 rem at the EAB and LPZ makes G3 PASS. The case is therefore labeled ATS under P0, and because an ATS exists, the plant falls under branch (iii) unless supported credit for active measures changes the G2 result under P1.

8. Conclusions and Future Work

This paper presented a traceable framework that combines the three ATS conditions of 10 CFR 73.100 as

gates evaluated on one plant state, scenario, damage state, and time axis; the final framework is described in Section 7 and Fig. 6. Each decision is traced upstream to the radiological consequence, initiating event, required function, and functional-loss logic, and downstream to the 10 CFR 73.100(a)(1) branch. The illustrative SLOCA case shows how the mitigation window and Point of No Return separate G2 from G3, and P0/P1 separation with the Undetermined result prevents unsupported ATS-absence claims.

Future work will proceed in five directions. First, the method will be implemented for a virtual facility and a reference SMR design and examined through pre-labeled cases, staged comparison, ablation, sensitivity analysis, and expert review. Second, because Level 1 PRA ends at core damage, a Level 2/3 consequence interface linking accident progression, source term, atmospheric dispersion, and dose will be developed, together with a method for quantifying the Point of No Return and the mitigation window. Third, CEAS and CEIS results from the RG 5.96 Three-Tier Analysis will be connected to G1 so that combined physical and cyber attack scenarios can be assessed under the same Case ID. Fourth, ATS outcomes will be linked to branch-specific application of the 10 CFR 73.100(a)(1) requirements and to vital area identification and protected area designation, refining the graded approach according to active-measure credit. Fifth, the results will be used to derive assessment items and evidence requirements for physical protection review guidance and acceptance criteria for advanced reactors in Korea, such as i-SMR.

ACKNOWLEDGMENT

This work was supported by the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (RS-2021-KN051410).

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