Automated F-C Curve Generation: (2) Consequence Quantification Using PCTRAN-RadPuff Coupling

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Abstract: This study, as a follow-up to the previous work, proposes a fully automated methodology for consequence quantification (radiological dose) and F-C (Frequency-Consequence) curve generation by directly leveraging event sequence frequencies automatically calculated in the preceding study. The previous work implemented automated event sequence generation and frequency quantification by coupling a dynamic event tree analysis with the PCTRAN, where sequence frequencies were obtained by combining initiating event frequencies with event tree branch (success/failure) probabilities. This follow-up study focuses on directly coupling those frequency results with consequence quantification.

Nuclear Energy Institute (NEI) 18-04 presents a Technology-Inclusive, Risk-Informed, and Performance-Based (TI-RIPB) methodology developed primarily for non-LWR reactor types, capable of providing an F-C analytical framework applicable to the licensing of advanced reactors across various reactor types, including LWRs (Light Water Reactors). Because a non-LWR plant model is not currently available in the simulator environment, the Korean OPR1000 model was adopted as the reference plant for implementing and demonstrating the proposed approach.

To enable efficient generation of the F-C curve by directly linking accident frequencies with dose-assessment results, this study develops an integrated platform by tightly coupling the nuclear power plant simulator PCTRAN with the radiological dose assessment code RadPuff. The platform employs UI-based automation and OCR-based data extraction to execute large numbers of scenarios and collect key outputs without manual intervention in a simulator environment with limited external data interfaces. After each sequence simulation in PCTRAN, the corresponding dose-related output is transferred to RadPuff, and the integrated TEDE (Total Effective Dose Equivalent) is automatically extracted. Finally, the F-C curve is automatically generated and saved as a log-scale plot by combining the final sequence frequencies (/Reactor Year) computed in the preceding study with the integrated TEDE dose results obtained from RadPuff. The proposed approach is expected to improve the efficiency, reproducibility, and consistency of result generation required for F-C-curve-based LBE selection and SSC safety classification under the NEI 18-04 framework.

Keywords: Automated PSA, Simulation, Frequency-Consequence curve

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1. INTRODUCTION

The risk posed by a nuclear power plant (NPP) depends jointly on how likely an accident is and on how severe its outcome would be, and a diagram that places each event by its frequency and its consequence captures this trade-off directly — a view especially suited to the rare but high-consequence accidents that dominate nuclear safety. Comparable frequency-versus-severity diagrams, such as frequency-number-of-fatalities (F-N) curves, are routinely used in the quantitative risk assessment (QRA) of other high-hazard facilities, including hydrogen refueling stations and chemical plants. In the nuclear field, an early and influential example was the Reactor Safety Study (WASH-1400), which combined accident probabilities, radioactive release, meteorology, and surrounding population into an overall measure of accident risk expressed as a complementary cumulative distribution function (CCDF) [2].

Probabilistic Safety Assessment (PSA) has become the principal means of generating and applying such risk information, conventionally organized into three levels — core-damage frequency, containment response and radioactive release, and the off-site dose and health effects from environmental transport. The dose quantification in the present work falls within this last, Level-3, scope.
Existing PSA and licensing practice, however, was built largely on light water reactor (LWR) experience, which may not transfer directly to advanced and next-generation reactors. As small modular reactors (SMRs) and non-LWR concepts move toward deployment, a flexible, technology-inclusive basis for demonstrating safety across very different designs becomes increasingly important. The Licensing Modernization Project (LMP) and Nuclear Energy Institute (NEI) 18-04 answer this need with a Technology-Inclusive, Risk-Informed, and Performance-Based (TI-RIPB) methodology [1], later accepted by the U.S. Nuclear Regulatory Commission in Regulatory Guide (RG) 1.233 [3]. The methodology places each Licensing Basis Event (LBE) on a single frequency-consequence (F-C) plane, whose position relative to a reference target drives the key decisions — which sequences are risk-significant, how safety functions and Structures, Systems, and Components (SSCs) are classified, and whether defense-in-depth is adequate.

Putting such a framework into practice is demanding: many initiating events and accident sequences must each be carried through a source-term and dose evaluation, and the whole exercise is usually repeated as the design evolves and as uncertainties are explored. Generating the F-C curve through a consistent, automated procedure is therefore an attractive way to keep these repeated evaluations both tractable and reproducible. The frequency-consequence curve generated in this study is hereafter referred to as the F-C curve, as distinct from the reference NEI 18-04 F-C Target introduced in Section 2.1.

Building an F-C curve requires both of its axes — the frequency of each event sequence and the corresponding radiological consequence. In a previous study, the authors automated the frequency axis: a dynamic event tree analysis tool (DICE [8]), in which a scheduler that performs the core functions of a dynamic PSA (DPSA) tool drives a plant simulator and branches the accident according to the simulated plant response, was coupled with the plant simulator PCTRAN as its physics module to generate event sequences and quantify the occurrence frequency of each. What remained unresolved was the consequence axis, and therefore the complete F-C curve. The present study is aimed at closing that gap. It builds on the fact that PCTRAN and the radiological dose-assessment code RadPuff, both developed by Micro-Simulation Technology, share a common data format: the per-sequence source term computed by PCTRAN is passed directly into RadPuff, the integrated Total Effective Dose Equivalent (TEDE) at the exclusion area boundary (EAB) is evaluated as the consequence, and pairing it with the previously quantified frequency produces the F-C curve through a single automated procedure. Because a suitable non-LWR thermal-hydraulic model was not available in the simulator environment, the Korean OPR1000 model was adopted as the reference plant, applying the non-LWR-oriented NEI 18-04 framework pre-emptively to an LWR. The main contributions are: (i) an automated PCTRAN-RadPuff consequence-quantification pipeline that operates within a closed, UI-based simulator environment using user-interface automation and optical character recognition (OCR); (ii) per-sequence extraction of the integrated TEDE at the EAB as the consequence metric; and (iii) end-to-end automated F-C curve generation, demonstrated on an OPR1000 hot-leg large-break loss-of-coolant accident (LLOCA) with 139 event sequences.

2. RESEARCH BACKGROUND

2.1. Frequency-Consequence (F-C) Target in NEI 18-04

On the F-C plane of NEI 18-04, each event sequence is represented by a pair of coordinates: its frequency of occurrence on the vertical axis, in events per plant-year, and its consequence on the horizontal axis. The consequence is taken as the 30-day Total Effective Dose Equivalent (TEDE) at the exclusion area boundary (EAB). The two coordinates originate from the two halves of the safety analysis. The frequency comes from the probabilistic side, where the initiating-event frequency is combined with the success or failure of the mitigating systems and operator actions. The consequence comes from the deterministic side, where a mechanistic source term — the radionuclide release implied by the accident progression — is carried through an atmospheric dispersion model to yield the dose at the EAB.

2.2. Overview of RadPuff

RadPuff is a radiological dose-dispersion projector developed by Micro-Simulation Technology [7], the same developer as PCTRAN. Because RadPuff belongs to the same simulation family, the time-dependent source term produced by PCTRAN is directly compatible with the input required by RadPuff, which provides a natural basis for coupling the two codes for consequence evaluation. RadPuff uses a Gaussian puff dispersion model: the radioactive release is discretized into a sequence of puffs, each advected by the wind field and dispersed according to atmospheric stability, and the code computes thyroid dose, whole-body dose, and TEDE at a selected receptor. RadPuff is operated through its graphical user interface and does not expose a direct external control or data-exchange interface, which, as described in Section 3, motivates a UI-automation and OCR-based coupling strategy.

2.3. Theory and TEDE Formulation in RadPuff

For a release discretized into puffs, let Q^i denote the activity of the i-th puff and let (x_p, y_p, z_p) and (x_r, y_r, z_r) be the locations of the puff center and the receptor, respectively. The Gaussian-puff spatial dispersion factor of the i-th puff, including ground reflection, is given by Eq. (1):

$$\begin{gathered}\Phi^i(x_r, y_r, z_r; T)\\ = \frac{Q^i}{(2\pi)^{3/2}{\sigma_y}^2\sigma_z} \cdot exp\left[-\frac{1}{2}\left(\frac{x_p - x_r}{\sigma_x}\right)^2\right] \cdot exp\left[-\frac{1}{2}\left(\frac{y_p - y_r}{\sigma_y}\right)^2\right] \cdot\\ \left(exp\left[-\frac{1}{2}\left(\frac{z_p - z_r}{\sigma_z}\right)^2\right] + exp\left[-\frac{1}{2}\left(\frac{z_p + z_r}{\sigma_z}\right)^2\right]\right)\end{gathered} \tag{1}$$

where σ_x, σ_y, and σ_z are the dispersion coefficients determined by the atmospheric stability class. Using this common kernel, the external deep dose equivalent (DDE) from the semi-infinite cloud and the committed effective dose equivalent (CEDE) from inhalation contributed by the i-th puff are given by Eqs. (2) and (3), respectively:

$$\mathrm{DDE}^i = \mathrm{DF}_{\mathrm{DDE}} \cdot \Phi^i \tag{2}$$

$$\mathrm{CEDE}^i = \mathrm{BRTH} \cdot \mathrm{DF}_{\mathrm{CEDE}} \cdot \Phi^i \tag{3}$$

where $\mathrm{DF}_{\mathrm{DDE}}$ and $\mathrm{DF}_{\mathrm{CEDE}}$ are the dose conversion factors for external exposure and for inhalation, respectively, and BRTH is the breathing rate. The dose conversion factors follow the formulations underlying U.S. EPA Federal Guidance Report No. 12 for external exposure [6] and Federal Guidance Report No. 11 for inhalation [5]. The TEDE at the receptor is the sum of the inhalation and external contributions over all puffs, as in Eq. (4):

$$\mathrm{TEDE} = \sum\nolimits_i \left(\mathrm{CEDE}^i + \mathrm{DDE}^i\right) \tag{4}$$

and the consequence value used for the F-C curve is the integrated TEDE accumulated at the EAB receptor over the exposure window, as defined in Eq. (5):

$$C_{\mathrm{EAB}} = \int_0^T \mathrm{TEDE}(x_{\mathrm{EAB}}, t)dt \tag{5}$$

In Eq. (5), T is the exposure window and $\mathrm{TEDE}(x_{\mathrm{EAB}}, t)$ is the instantaneous TEDE at the exclusion-area-boundary (EAB) receptor at time t. The receptor is fixed at the EAB downwind distance x_{EAB}, on the plume centerline (zero crosswind offset) and at ground level (zero elevation) — the maximally exposed boundary location — so that C_{EAB} is the time-integrated TEDE accumulated there over the exposure window.

In NEI 18-04 the consequence is defined as the 30-day integrated TEDE at the EAB. The exposure window in the present pipeline is user-defined, so each sequence can be integrated over whatever duration the analyst wishes to evaluate, up to the full 30 days. For this study a 12-hour window was adopted, chosen by considering the coupled simulator environment and the per-sequence run time over the large number of sequences, and also so that the consequence-integration window coincides with the 12-hour mission time used to terminate each sequence in the preceding dynamic event tree analysis; the resulting 12-hour integrated TEDE is used as the consequence metric here. Because the window is a user-set parameter, extending the evaluation to the full 30-day TEDE requires no change to the procedure itself.

2.4. Event-Sequence Classification and Source-Term Hand-off

In the previous study, the dynamic event tree analysis produced, for each accident sequence, the time-dependent plant response and the associated source term from the PCTRAN source-term model [4]. PCTRAN tracks fission-product generation, transport, and release across the successive barriers (fuel pellet and cladding, reactor coolant system, steam generator secondary side, and containment), and links the clad failure fraction (FRCL) and gap release to the coolant and containment radionuclide inventories. For the OPR1000 model this draws on a built-in dataset of 52 nuclides, each carrying its fuel/core inventory, gap- and release-related coefficients, half-life, mean gamma energy, dose conversion factors, and the initial equilibrium activity concentrations in the reactor coolant and on the steam-generator secondary side, all used here at their default values. The output for each sequence is written as a Microsoft Access database (*.mdb) dose file.

In the previous study each sequence frequency was obtained as a distribution rather than a single value, summarized by its mean and 5th-/95th-percentile bounds; the present analysis consumes these directly, with the mean fixing each point's vertical position on the F-C plane and the percentiles setting its uncertainty bar. Each sequence was also assigned a final state — Normal (N), Core Damage (D), or one of three non-terminal outcomes (Cutoff, Unknown, or Branch-point). Only the sequences that reach a determined N or D state are carried forward and assigned a consequence here.

For quantification, the 139 sequences are grouped into two classes according to their final plant state: N (Normal), i.e., sequences that are terminated without core damage, and D (Core Damage). For N sequences the cladding remains intact, so the released activity corresponds to the normal-operation, technical-specification coolant activity carried by the PCTRAN model as the initial equilibrium reactor-coolant and steam-generator activity, and is essentially independent of the detailed thermal-hydraulic path; consequently these sequences yield a small, fixed integrated TEDE. For D sequences the source term is governed by the extent of core damage and therefore spans a wide range of magnitudes. Each dose file is handed off to RadPuff as the input source term for the dispersion and dose calculation.

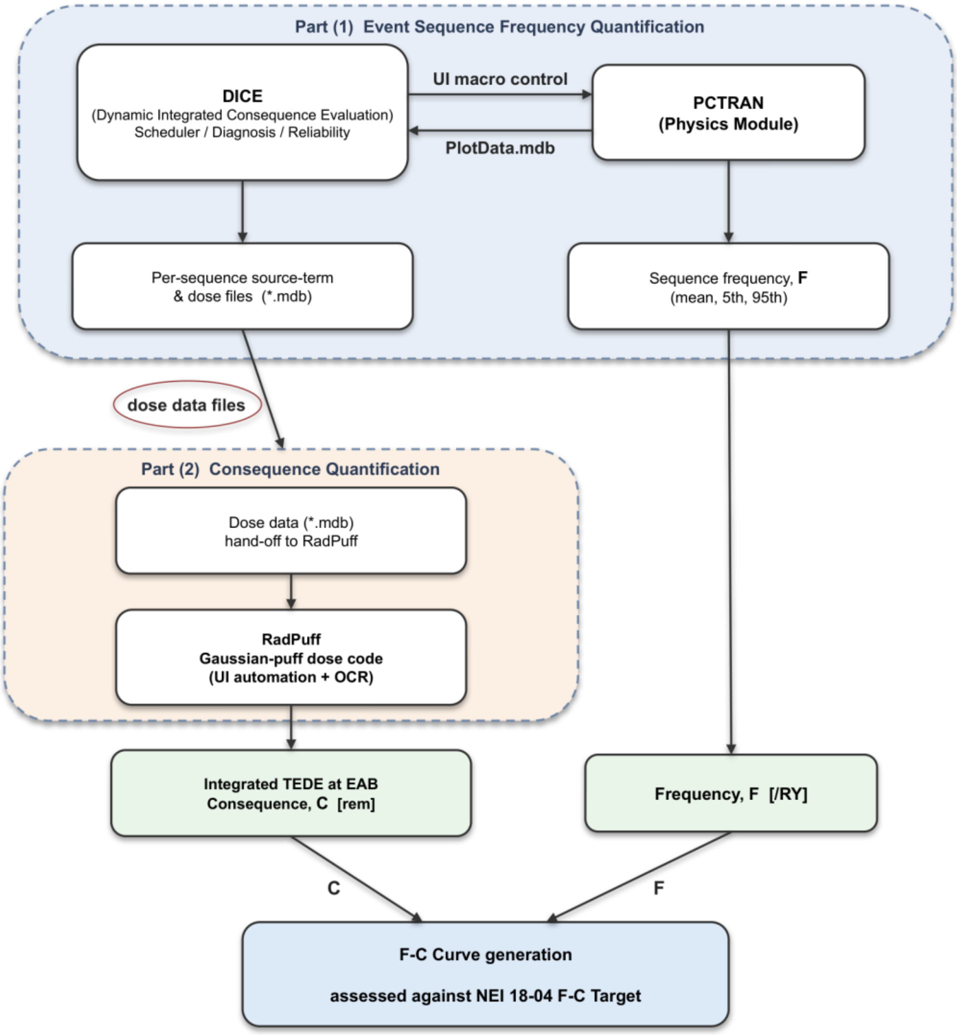
3. PCTRAN-RADPUFF COUPLING AND AUTOMATION

3.1. Coupling Architecture

Figure 1 shows the integrated DICE-PCTRAN-RadPuff architecture that spans the two studies. In the previous study, DICE controlled PCTRAN as its physics module through a user-interface macro and read the plant response from the PCTRAN output database, producing for every sequence both a source-term/dose file and a quantified frequency (mean, 5th, and 95th percentiles). The present work begins from those outputs: each PCTRAN dose file is handed off to RadPuff, which evaluates the integrated

TEDE at the EAB as the consequence C, while the corresponding frequency F is taken from the previously computed results. Pairing F and C over all sequences yields the F-C curve, which is then assessed against the NEI 18-04 F-C Target. The shared data format between PCTRAN and RadPuff makes the source-term hand-off direct, but because RadPuff exposes no external programming interface, the coupling is implemented at the user-interface level.

Figure 1. DICE-PCTRAN-RadPuff architecture for automated F-C curve generation

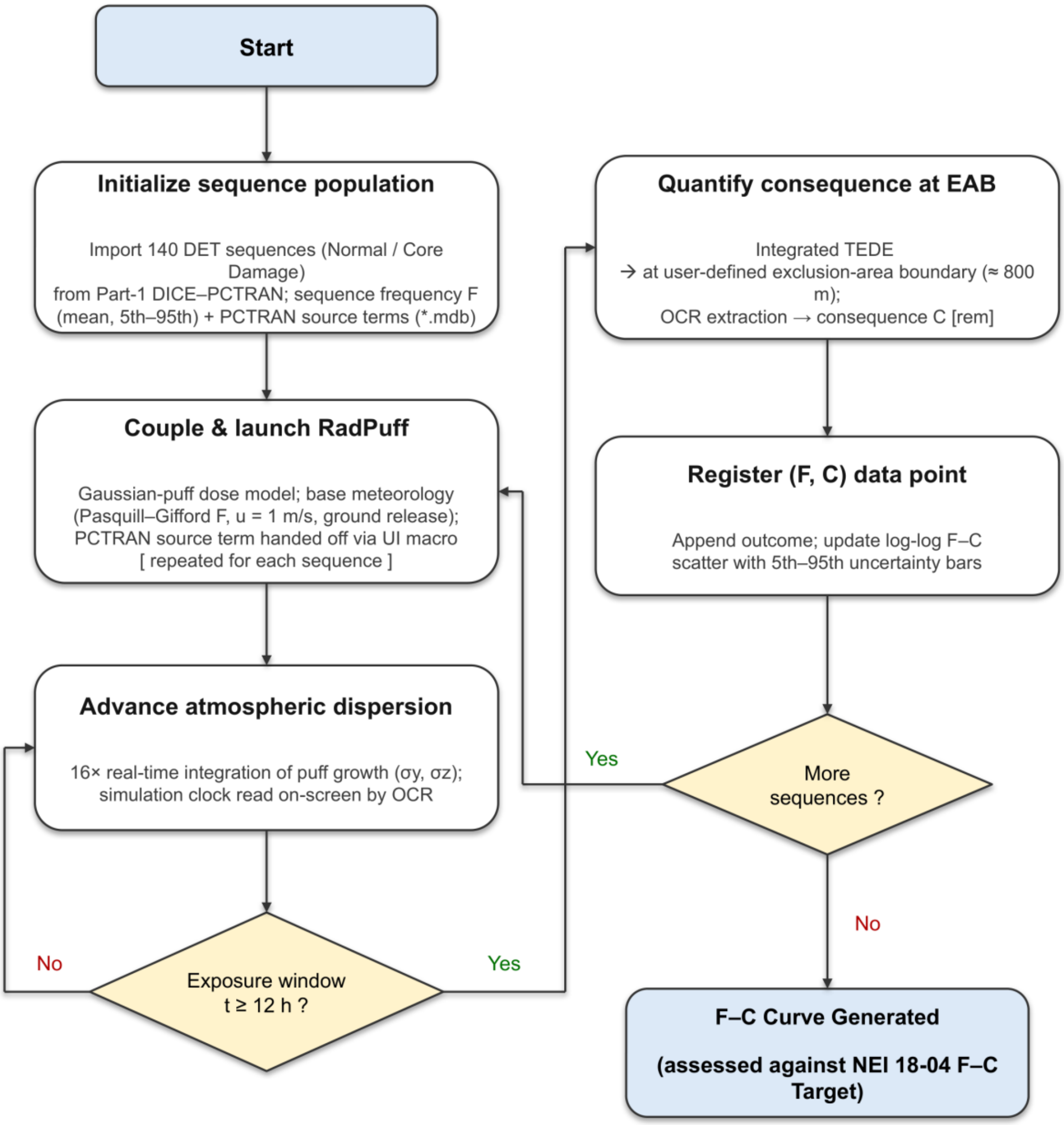


3.2. Automated Execution via UI Automation and OCR

Because RadPuff is a UI-based simulator without a direct external data interface, the dose calculation is automated by emulating user mouse and keyboard operations rather than by controlling the code at the programming level. Screen actions are issued at recorded absolute coordinates, and the coordinate set is user-definable so that site- and unit-specific points can be reconfigured without changing the program logic. In particular, the EAB receptor is specified as a user-defined absolute coordinate, because the EAB location differs by site and by unit; in this study the EAB receptor was placed at a distance of approximately 800 m for the OPR1000 case.

Figure 2 summarizes the workflow. The user scans the data folder for the dose files (*.mdb) and loads the per-sequence frequencies (mean, 5th, and 95th percentiles) produced in the previous study. For each sequence it launches RadPuff, selects the dose file, confirms the radiation source, sets the release period, accelerates the run to 16×, and starts the dispersion calculation. The on-screen simulation timer is read repeatedly by OCR and the run is advanced until the 12-hour target time is reached. The user then clicks the user-defined EAB point and reads the integrated TEDE value [rem] by OCR; a numeric-normalization routine corrects common OCR confusions and reconstructs scientific notation so that the dose is captured reliably without manual intervention. Each result is appended to a memo file together with the sequence frequency, and the F-C plot is updated incrementally. The meteorological condition uses the RadPuff default base case: a wind speed of 1 m/s heading south, no precipitation, a ground-level release at zero elevation, and atmospheric stability class F (moderately stable).

Figure 2. Automated PCTRAN-RadPuff and F-C curve generation workflow.



3.3. F-C Curve Generation

For every processed sequence, the consequence C (the integrated TEDE at the EAB) is paired with the frequency F obtained in the previous study to form one point on the F-C plane. The points are plotted on logarithmic frequency and consequence axes, and a vertical error bar derived from the 5th and 95th percentile frequencies is attached to each point to convey the frequency uncertainty. Because the entire procedure - from scanning the data folder to producing the final figure - is executed without manual intervention, the curve can be regenerated consistently whenever the underlying sequences or their frequencies are updated.

4. CASE STUDY: OPR1000 HOT-LEG LLOCA

The approach was demonstrated on the OPR1000 model of PCTRAN with a hot-leg large-break loss-of-coolant accident (LLOCA) as the initiating event. The reference plant state is the 100%-power end-of-cycle condition of the OPR1000 model (rated thermal power 2,815 MWt, primary pressure about 15.5 MPa, average coolant temperature 311.2 °C, primary flow 15,309 kg/s, and steam-generator pressure 7.8 MPa). The dynamic event tree analysis of the previous study produced 139 event sequences with a determined end state, of which 100 were classified as N (Normal, terminated without core damage) and 39 as D (Core Damage). Each sequence was simulated in RadPuff for 12 hours under the default base meteorological condition, with the EAB receptor placed at approximately 800 m, and the integrated TEDE at the EAB was extracted as the consequence value. Consistent with that analysis, for this hot-leg LLOCA the containment-leakage path is the dominant external release path, as steam-generator-tube and turbine-building release paths are not significant in the scenarios considered.

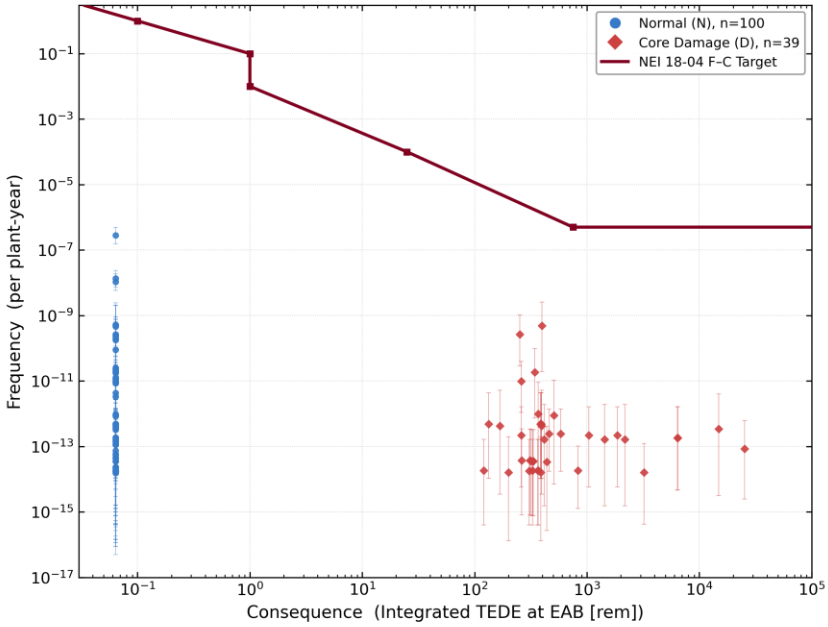
Table 1 summarizes the results by sequence class. All 100 N sequences yield the same integrated TEDE of 0.0637 rem: with the cladding intact, the released activity corresponds to the fixed normal-operation equilibrium activity of the reactor coolant and steam generators carried by the PCTRAN model (bounded by the Technical Specification limit of about 0.1% of the fuel gap content), independent of the detailed thermal-hydraulic progression. The 39 D sequences, in contrast, produce integrated TEDE values spanning more than two orders of magnitude, from about 1.2×10^2 to 2.53×10^4 rem, reflecting the dependence of the core-damage source term on the accident progression.

Table 1. Integrated TEDE at the EAB by sequence class (OPR1000 LLOCA, 139 sequences)

Class	Description	No. of sequences	Integrated TEDE at EAB [rem]
N	Normal (no core damage)	100	0.0637 (constant)
D	Core damage	39	1.2×10^2 – 2.53×10^4

Figure 3 shows the resulting F-C curve. The points form two distinct clusters: the N (Normal) sequences accumulate at the fixed low consequence of 0.0637 rem, while the D (Core Damage) sequences populate the high-consequence region. The frequency values are the per-sequence frequencies obtained from the previous dynamic event tree analysis, so individual sequences have low frequencies, with the error bars indicating the 5th-to-95th-percentile range. Plotting the curve against the NEI 18-04 F-C Target (the burgundy line through the regulatory anchor points) allows the risk significance of the sequences to be assessed on the same risk-informed basis used for LBE selection and SSC safety classification. For this case study all 139 sequences lie well below the F-C Target, so none approaches the risk-significance boundary; the large vertical margin is consistent with the low per-sequence frequencies produced by the dynamic event tree, and the N and D clusters are separated by more than five orders of magnitude in consequence.

Figure 3. Automatically generated F-C curve (OPR1000 hot-leg LLOCA 139 N/D sequences)



5. CONCLUSION

This study developed an automated consequence-quantification pipeline that tightly couples the plant simulator PCTRAN with the radiological dose-assessment code RadPuff, and used it to generate the F-C curve end to end together with the event-sequence frequencies quantified in the authors' previous study. By emulating the user interface and extracting on-screen results through OCR, the pipeline executes a large number of sequences and collects the integrated TEDE at the EAB without manual intervention, even though RadPuff provides no external data interface. The approach was demonstrated on an OPR1000 hot-leg LLOCA with 139 sequences, for which the no-core-damage (N) sequences yield a constant low consequence and the core-damage (D) sequences span a wide consequence range; each point carries the 5th-to-95th-percentile frequency uncertainty propagated from the previous dynamic event tree analysis.

Beyond automating individual steps, the proposed pipeline closes the loop between probabilistic frequency quantification and deterministic dose assessment within a single procedure, so that the same mechanistic source term that governs the plant response also drives the consequence calculation. The full 5th/mean/95th frequency uncertainty from the dynamic event tree is thereby carried through to the F-C plane rather than collapsed to point estimates. Because the coupling is realized through UI automation and OCR rather than a code-level interface, the method extends integrated deterministic-probabilistic safety assessment to closed, GUI-only simulators that expose no external programming interface, and regenerates the entire curve consistently whenever the underlying sequences or frequencies change.

The automated procedure improves the efficiency, reproducibility, and consistency of the result generation required for F-C-curve-based LBE selection and SSC safety classification under the NEI 18-04 framework, and applies that non-LWR-oriented framework pre-emptively to an LWR using an existing OPR1000 simulator model. Several limitations remain: the PCTRAN source-term model is less detailed than dedicated severe-accident codes such as MELCOR or MAAP; a single base-case meteorological condition was used; and the coupling depends on UI automation and OCR. Future work will extend the framework to a non-LWR thermal-hydraulic model, evaluate the consequence over the full 30-day TEDE window, incorporate meteorological and source-term uncertainty, and pursue a more seamless DICE-PCTRAN-RadPuff coupling.

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