

Analysis of the Components within Frequency-Consequence Curve and Implementation for Probabilistic Safety Assessment

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1. Introduction

With rising interest in advanced and small modular reactors and potential deployment in the near future, it is essential that a robust regulatory framework exists for ensuring the safety of such reactors. However, pre-existing nuclear regulatory frameworks are formulated around light water reactors (LWR) and are structured in a prescriptive manner. These pre-existing deterministic safety approaches are inappropriate for advanced design reactors such as molten-salt reactor (MSR) and high temperature gas-cooled reactor (HTGR) whose operating system differs greatly from the conventional LWR. In addition, conventional framework relies heavily on conservative assumptions and analysis which can place significant burden on construction timeline and financial requirement. As a result, there has been continuous efforts to overhaul the regulatory framework for a more robust and structured safety assessment framework which accommodates a variety of innovative nuclear reactor designs. This ideology culminated in the U.S. NRC 10 CFR part 53 [1] which establishes a technology-inclusive, risk-informed, performance-based (TI-RIPB) framework as an alternative for regulating new commercial nuclear power plants.

The TI-RIPB regulatory framework is a safety approach that evaluates safety based on estimated risk and performance outcomes instead of prescriptive, technology-specific requirements or conditions. The three key elements of the regulatory framework are:

- Technological inclusiveness, which allows diverse and novel designs to be assessed on their own safety merits
- Risk-informed analysis, which uses probabilistic and deterministic methods to identify and prioritize significant hazards
- Performance-based criteria, which set measurable safety targets while leaving the means of achieving them flexible

These three elements allow the regulatory framework to maintain a rigorous and logical safety standard with flexibility accommodating innovative technologies. One key reason for the development of TI-RIPB was due to conventional safety approach having significant reliance on surrogate risk objectives like core damage frequency and have been centered around LWR technology. These requirements may not be applicable for certain

advanced reactor design. As a result, TI-RIPB approach no longer focuses on surrogate risk objectives and instead proposes the use of Frequency-Consequence (F-C) curve for probabilistic safety assessment (PSA). Safety assessment of a nuclear power plant can be improved by utilizing F-C curve as an analytical tool to present a quantified graphical representation of acceptable risk.

2. Frequency-Consequence Curve

Implementation of F-C curve in the TI-RIPB framework was first introduced in NEI 18-04 [2] as a graphical risk-assessment tool used to characterize and evaluate the acceptability of accident sequences in a nuclear facility. The F-C curve as shown in Fig. 1 is a log-log plot of accident sequence frequency against the magnitude of radiological dose consequence. The curve interweaves fundamental concepts from probabilistic safety assessment and regulatory criteria to better evaluate safety and risk of a nuclear facility.

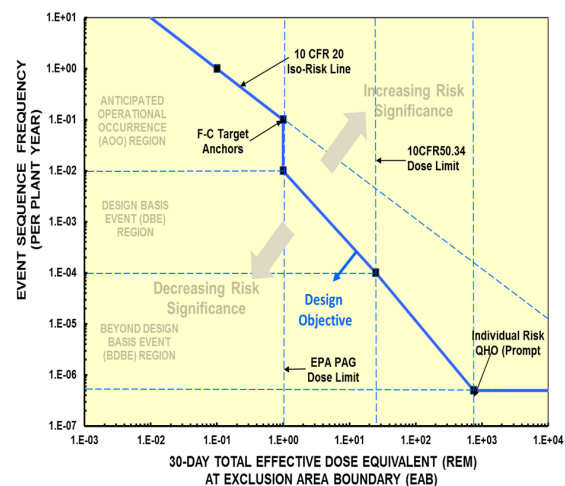


Fig. 1. Frequency-consequence curve illustration [2]

The underlying principle of the F-C curve is that acceptable risk is inversely proportional to consequence severity: high-frequency events must be limited to low-consequence outcomes, whereas events with potentially severe consequences must be constrained to correspondingly low frequencies. Coupled with the

target line formulated based on regulatory criteria, an acceptable risk profile can be established to support analysis of the risk significance of accident sequences for a nuclear power plant. While use of F-C curve has been endorsed by U.S. NRC, there are still significant areas for consideration in the implementation of F-C curve. Decision makers and regulatory bodies would have to be properly informed of the nuances within the F-C curve to ensure optimal usage and application in their national context.

In this study, the components of F-C curve will be individually analyzed, and some key considerations will be highlighted. Offsite consequence analysis modeling with MELCOR Accident Consequences Code System (MACCS) [3] with some event sequences from SOARCA report [4] will be utilized to discuss aspects related to event consequence in the F-C curve.

3. F-C Curve Components and Regional Implementation

The F-C curve comprises of the axes, target line, risk significant region and the licensing basis event (LBE). While LBE determination is critical for the implementation of F-C curve, the content is plant specific and rooted in probability safety assessment (PSA) which is difficult to discuss within this short study. Similarly, risk significance is largely rooted in risk acceptance and quantification of health objectives which are complex subjects that are challenging to discuss within the scope of this study. As such, this study will only focus on the axes and target line which form the basis of F-C curve. The following discussion will be segmented into individual sections to ensure informed implementation of F-C curve.

3.1. Event Frequency – Y-axis

The y-axis of the F-C curve is represented by the mean frequency per plant year for event sequences. The mean frequency per plant year is calculated from Level 1 and 2 PSAs and does not include the frequency from Level 3 PSA. This event sequence frequency should not be confused with conventional surrogate risk metrics such as core damage frequency and large early release frequency. The event sequences are solely a measure of frequency of event occurrence and not dependent on the condition of event sequence consequences such as core damage and large early release. Thus, application of conventional risk metrics from Level 1 and 2 PSAs in F-C curve should be considered with care.

3.2. Event Consequence – X-axis

The x-axis of the F-C curve is represented by the mean radiation dose consequences from the event sequences. This is characterized by the total effective dose equivalent (TEDE) at the exclusion area boundary (EAB) over 30 days. The result is calculated from Level 3 PSA based on outputs from Level 1 and 2 PSAs. The

TEDE includes exposure pathways such as cloudshine, groundshine and inhalation. Two factors of the y-axis for F-C curve definition should be treated with attention. Firstly, the definition of 30-day TEDE was defined by the NEI 18-04 report, and this can have notable impact on the implementation of F-C curve. The 30-day period was meant as an encompassing period that would capture the consequences derived from the whole accident sequences. There are no clear regulatory criteria that correspond to the recommended period. The assessment period could be changed for specific implementation of F-C curve, but it should be noted that a short assessment period may be unable to capture significant portion of the consequences from an event sequences. Three events sequences from SOARCA report were extracted to illustrate this consideration. Fig. 2 depicts the plot of percentage mean consequence against assessment duration in days. The percentage mean consequence was obtained by dividing the TEDE at each assessment duration against the total TEDE accumulated from a one year assessment period. This provides an illustration of how the selection of assessment period affects the representation of the radiological impact from the accident sequence. As a simple illustration, the exposed individual is assumed to remain in place without any emergency protective intervention.

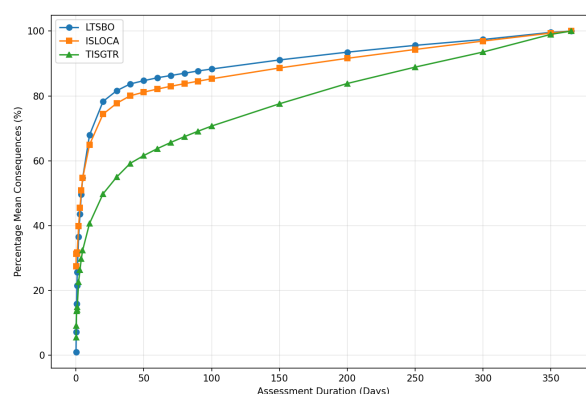


Fig. 2. Percentage mean consequence against assessment duration

It can be observed from the Fig. 2 that the proper selection of assessment duration can significantly affect the mean consequences from an accident sequence. A sufficiently long assessment period can ensure proper accounting of the radiological consequence. An overly short assessment period of two hours may under-represent the overall consequence of the accident. Consequences of different accident sequences also evolve differently over assessment period due to differences in release duration and radionuclide content.

Fig. 3 provides the radionuclide contribution of radiological consequence for a 30-day, and 1-year assessment period based on radionuclide category. Similarly, the study was based upon the different accident sequences, and the result are percentage

contribution of each radionuclide relative to the total TEDE for specific sequences and assessment duration. The major contributors for radiological dose consequences for a 30-day assessment period are iodine and tellurium as seen in Fig. 3. It is notable that some conventional closely monitored radionuclides like cesium may have a smaller impact within a 30-day assessment period. The impact of such assessment typically focuses on the early exposure impact and tends to under-represent the long half-life radionuclides which will be more significant over a longer period. Hence, the assessment period should be appropriately selected based on regulatory criteria and requirements.

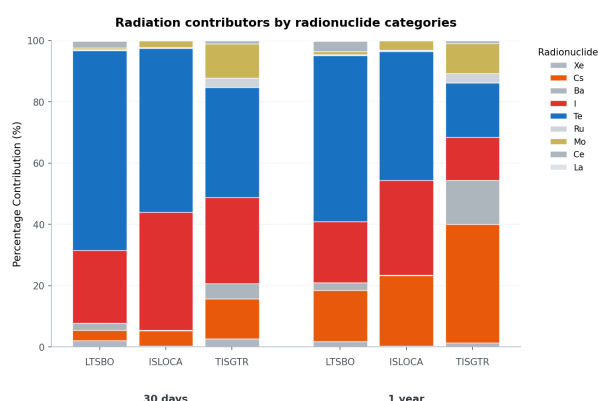


Fig. 3. Radionuclide contribution for 30 days and 1 year

The second consideration would be the definition of EAB which was defined in U.S. NRC 10 CFR part 53 as “the exclusion area surrounding the reactor where an individual located at any point on the boundary should not receive a radiation dose of 250 mSv for any 2-hour period from a design-basis accident”. Determination of the EAB will be dependent on the regulatory criteria, site specification and other factors. Generally mean dose consequences are inversely proportional to assessment distances. Thus, overly conservative determination of EAB may mask risk significant events and the reverse could be true too.

3.3. Target Line

The target line in the F-C curve is an isodose line that is characterized by target anchors determined via regulatory criteria. These anchor points are derived based on LBE categories and loosely based on regulatory frameworks. The LBE categories are anticipated operational occurrences (AOOs), design basis events (DBEs) and beyond design basis events (BDBEs). The anchor points in the NEI 18-04 are shown in Table I. These values serve to define the shape of F-C curve target line that defines the risk profile.

Table I. NEI 18-04 F-C Curve Target Anchors Points

Category	Frequency range (plant yr ⁻¹)	Consequence (mSv)
AOO	> 1E-1	<10
AOO	1E-2 - 1E-1	10
DBE	1E-4 - 1E-2	250 -10
BDBE	5E-7 - 1E-4	7500 - 250

These anchors points represent coordinate points for the target line, and isodose relationship are formulated between these anchor points. The frequency range is defined based on the typical regulatory categorization while consequence of the target anchors is roughly based on U.S. regulatory criteria. Table II provides the corresponding basis and the context within the U.S. regulatory context as an example.

Table II. NEI 18-04 F-C Curve Target Anchors Points Regulatory Basis and Context

Category	Regulatory basis	Context
AOO	10 CFR 20	Public dose limit
AOO	US EPA PAG	Protective action limit
DBE	10 CFR part 53.210	EAB definition
BDBE	Quantifiable Health Objective (QHO)	Surrogate value for QHO

For the implementation of F-C curve for a specific national context, it is important for the user to define appropriate corresponding target anchors. Typically, the target anchor point associated with public dose limit and protective action limit are well defined with abundance of documents from international bodies. The latter two target anchor points are associated with national regulatory definition. For example, the consequence value for BDBE in the original documentation was determined based on the QHO that limits the associated latent cancer risk to 2E-6 per reactor year. Such QHO surrogates will have to be determined based on local context and regulatory criteria. It will be critical for decision makers to introduce suitable regulatory basis for the latter two target anchors based on local regulatory criteria and other local conditions.

3.4. Other Considerations

Lastly, certain countries have specific pre-existing safety goals for Cs-137 which may be difficult to coincide with the F-C curve. The foundation of such safety goal is based on conventional light water reactor design and may not be a good fit for technological inclusive safety approach. However, it should also be noted that the current implementation of F-C curve may face limitations in representing the radiation dose consequence from long half-life radionuclide like cesium. If long half-life radionuclides are of particular concern, additional assessment with F-C curve utilizing a long assessment period may be considered. As seen in Fig. 3, the contribution of radiation dose from cesium category can be accounted to a greater degree by increasing the assessment period. Thus F-C curve

assessment with a longer assessment period may be viable option to represent consequences associated with long half-life radionuclides. However, target anchors points should be selected appropriately to reflect such changes. It should also be noted that long half-life radionuclides have alternative exposure pathways such as ingestion pathways that may be difficult to accurately model.

4. Conclusion

Implementation of F-C curve will be an important part of safety assessment for future nuclear reactors. This study provides insights over the implementation of F-C curve particularly over the selection of assessment period, the potential under-representation of certain accident sequences and the associated radionuclide contribution. Application of F-C curve should consider such potential issues to ensure the safety assessment of a nuclear power plant can be completed in a robust and comprehensive manner.

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REFERENCES

- [1] U.S. NRC, Risk-Informed, Technology-Inclusive Regulatory Framework for Commercial Nuclear Plants, 10 CFR part 53, 2026
- [2] NEI, RIPBTI Guidance for Non-Light Water Reactor Licensing Basis Development, NEI 18-04 Rev, 2019
- [3] Sandia National Laboratories, MELCOR Accident Consequence Code System (MACCS) Users Guide (V.4.2), Sandia National Laboratories, SAND2023-01315, 2024
- [4] U.S. NRC, State-of-the-art Reactor Consequence Analyses Project Volume 2: Surry Integrated Analysis, NUREG/CR-7110, Vol. 2, Rev. 1, 2013
- [5] International Atomic Energy Agency, Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. NS-R-3 (Rev.1), 2016