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

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NUS National University of Singapore | Singapore Nuclear Research and Safety Institute

KAERI Korea Atomic Energy Research Institute

Background

- Need for modernization of regulations
  - Existing regulation designed around large LWR
  - Regulation may not be suitable for advanced reactors
  - Immense burden on applicants for permits
- Movement for modernization
  - US. NRC introduce 10 CFR part 53 on April 2026
  - Regulatory implementation of TI-RIPB
    - Technology Inclusive (TI): Valid for all technology
    - Risk Informed (RI): Consider PSA insights
    - Performance Based (PB): Focus on achieving safety outcome
- Regulatory guide 1.233 and NEI 18-04 guidance on TI-RIPB
- Frequency-Consequence (F-C) curve as an analytical tool

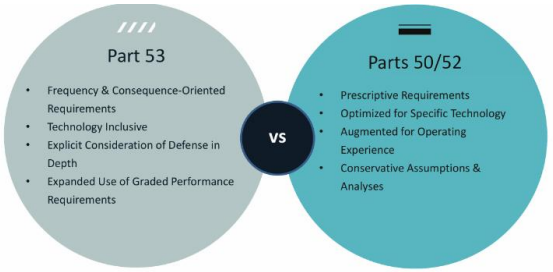


Figure 1.
TI-RIPB framework differences

F-C curve

- Plots the relationship between **frequency** and **consequences**
  - Limit line defining acceptable risk profile
    - Event above limit line is unacceptable
    - Highlight risk significant accident sequences
  - Allows evaluation of Licensing Basis Events (LBE)
- Analysis to support formation of nation specific F-C curve

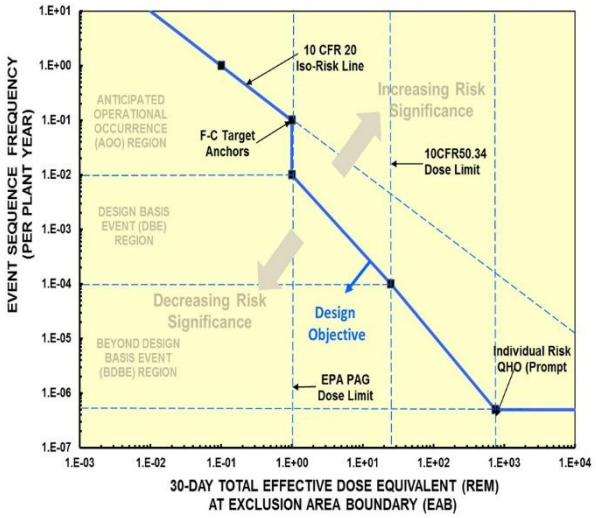


Figure 2. NEI 18-04 F-C curve

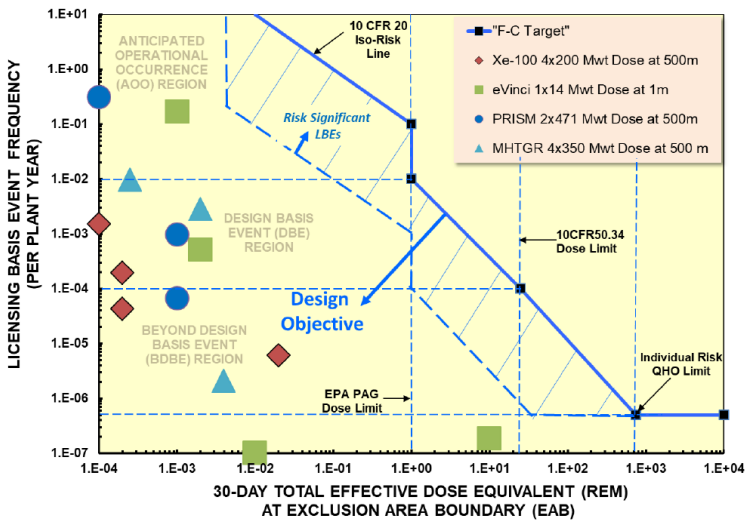


Figure 3. LMP F-C curve demo

Components of F-C curve

- F-C curve components
  1. Y-axis: frequency
  2. X-axis: consequence
  3. Target anchor
  4. LBE data
  5. Risk significance
- Key features
  - Straight line on log-log graph
  - Anchor points used to define shape of F-C curve
  - Provide risk profile and acceptability of LBE

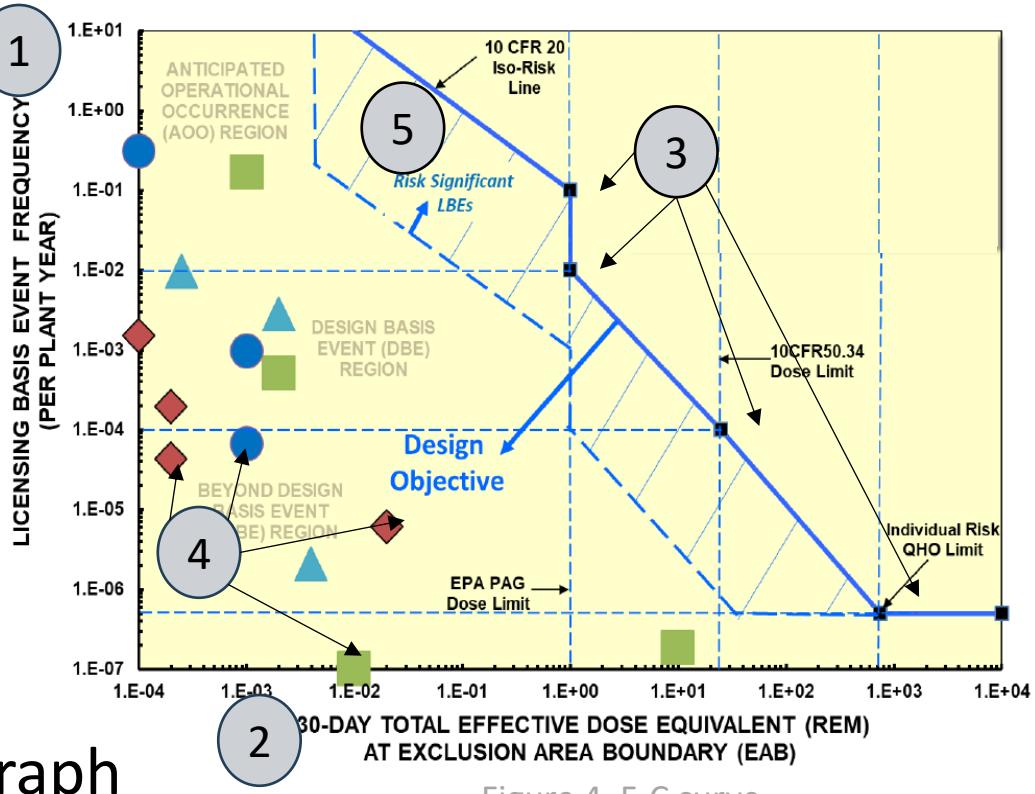


Figure 4. F-C curve

Components of F-C curve

1. Y-axis

- Event frequency
  - Event sequence mean frequency (per plant year)
  - Plant year instead of reactor year
  - Based on Level 1 and Level 2 PSA
- Used to classify LBE into each categories
  - Familiar metric from PSA with CDF and LERF
    - Not conditional on consequence
    - Not significantly different
- Mean value should be used
    - Any event which 5th and 95th percentile straddles a frequency boundary is evaluated for both categories

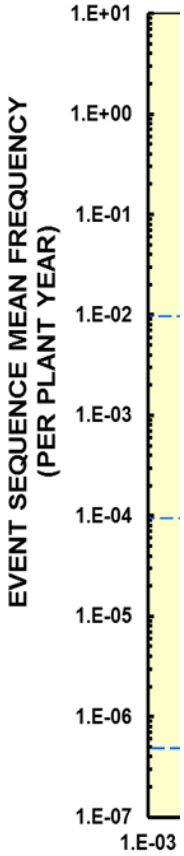


Figure 5. F-C curve Y aixs

Components of F-C curve

2. X-axis

- Event consequence
  - 30-Day TEDE at Exclusion Area Boundary (EAB)
  - Radiation dose consequences calculated from Level 3 PSA
  - Traditional regulatory focus for early/acute risk
- Total effective dose equivalent (TEDE)
  - Cloudshine, groundshine & inhalation dose pathways
  - Potential for change due to recent alignment
  - Acceptance of total effective dose based on ICRP definition

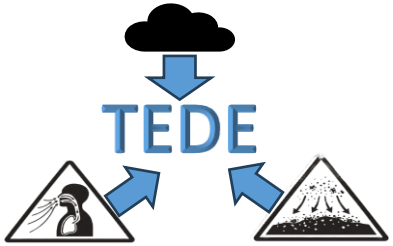


Figure 6. TEDE

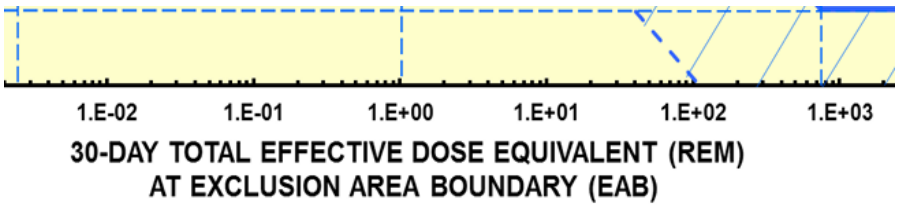


Figure 7. F-C curve X axis

Components of F-C curve

- 30-Day proposed by NEI 18-04
- Differs from U.S. NRC acceptance criteria
  - Lack of definitive regulatory basis
- Emergency preparedness (96 hours) or siting (2 hours)
- Regulatory requirement more stringent
- Careful consideration when constructing F-C curve

Phase	Protective Action Recommendation	PAG, Guideline, or Planning Guidance
Early Phase	Sheltering-in-place or evacuation of the public[b]	**PAG**: 1 to 5 rem (10 to 50 mSv) projected dose over four days[c]
	Supplementary administration of prophylactic drugs – KI[d]	**PAG**: 5 rem (50 mSv) projected child thyroid dose[e] from exposure to radioactive iodine
	Limit emergency worker exposure (total dose incurred over entire response)	**Guideline**: 5 rem (50 mSv)/year (or greater under exceptional circumstances)[f]

Figure 8. EPA PAG standard

An individual located at any point on the boundary of the exclusion area for any 2-hour period following the onset of the postulated fission product release would not receive a radiation dose in excess of 25 rem (250 millisieverts) total effective dose equivalent (TEDE); and

Figure 9. 10 CFR part 53

Components of F-C curve

- Assessment duration can affect mean consequences
  - 30-day may not capture consequences equally
  - Accident progress differently
  - Overly short assessment period may under represent impact

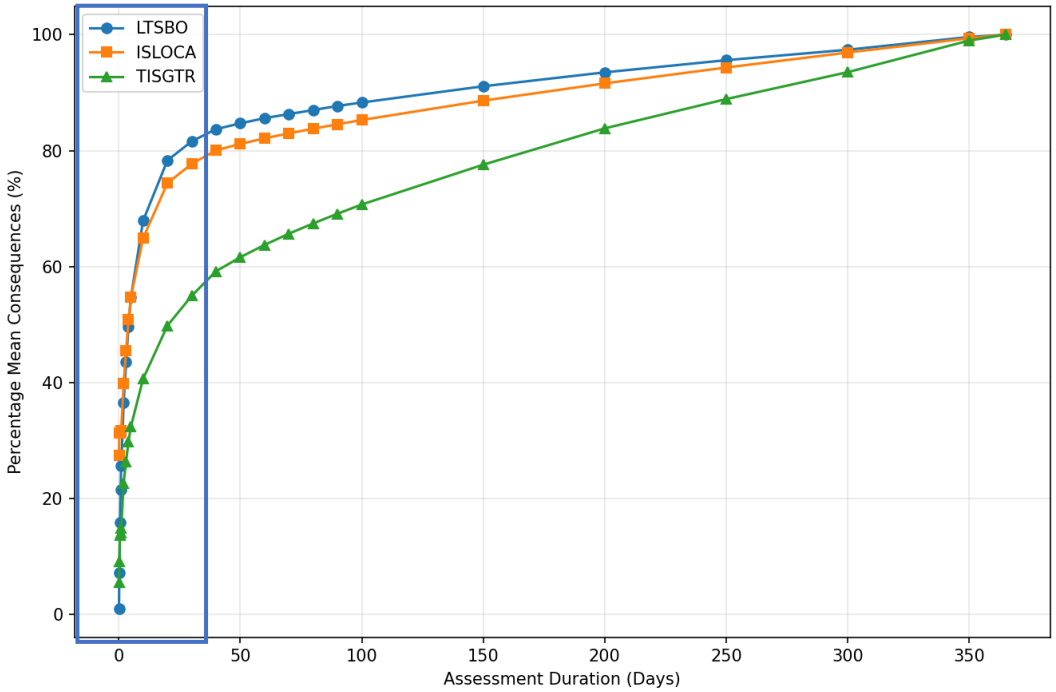


Figure 10. Percentage mean consequence against assessment duration

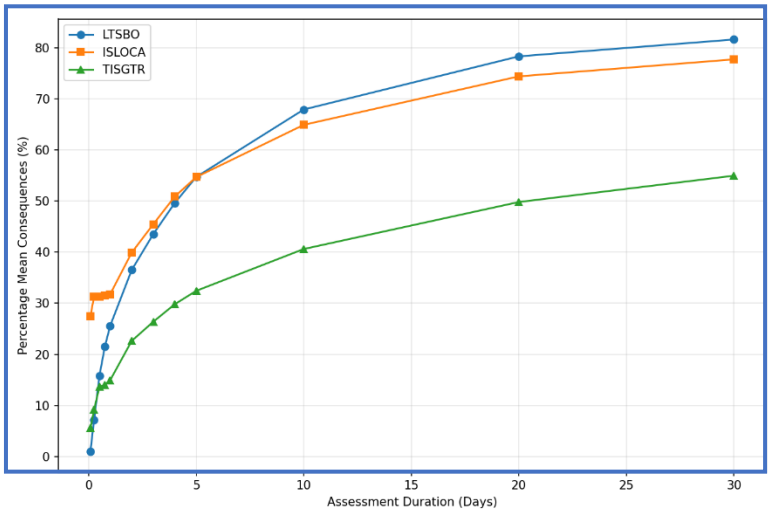


Figure 11. Closed up version (<30 days)

Components of F-C curve

- Radionuclide contribution also varies
  - For 30-day assessment period
    - Under represent long half-life radionuclides
  - For longer assessment period
    - Higher contribution from long lived radionuclides

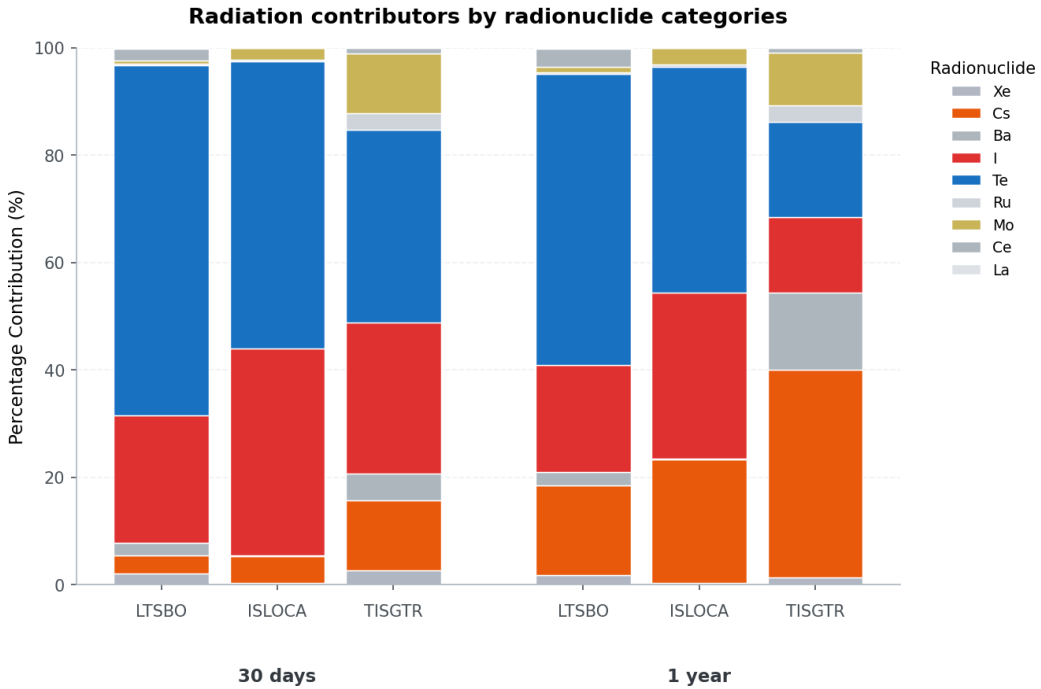


Figure 12. Radionuclide contribution for 30 days and 1 year

Components of F-C curve

- Exclusion Area Boundary (EAB)
  - Dependent on regulation and reactor type
  - Consequence inversely proportional to assessment distance
  - Operational burden but good for safety
  - Further complicated by multi unit site

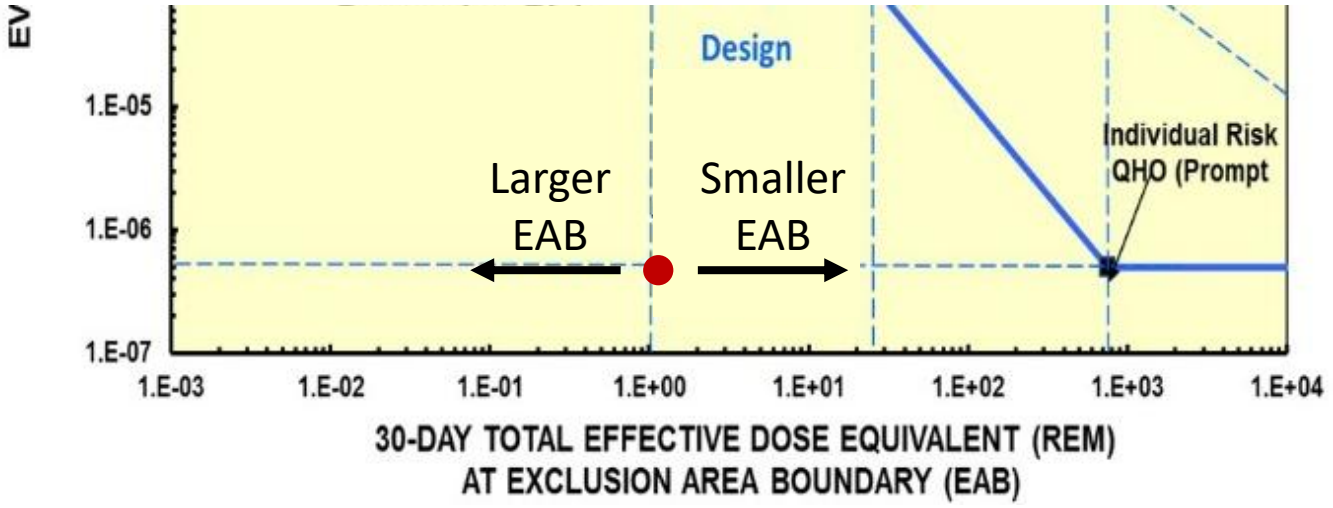


Figure 13. EAB impact on mean consequences

Components of F-C curve

3. Target anchor

- straight line that is characterized by target anchors

Category	Regulatory basis	Context
AOO	10 CFR part 20	Public dose limit
AOO	U.S. EPA PAG	Protective action limit
DBE	10 CFR part 53	EAB definition
BDBE	Quantifiable Health Objective (QHO)	QHO surrogate value

Table 1. NEI 18-04 F-C Curve Target Anchors Points Regulatory Basis and Context

Table 2. Korea regulatory basis

Category	*Regulatory basis for consequence*
AOO	***Article 2***
AOO	***Article 15***
DBE	***Article 6 & article 8***
BDBE	***???***

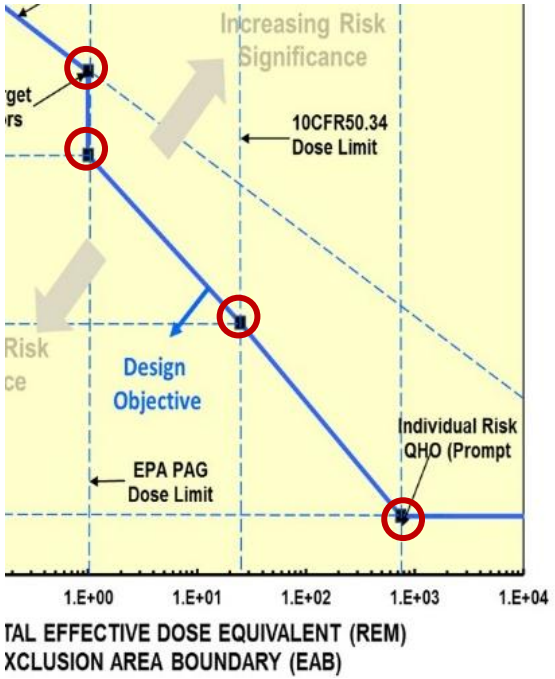


Figure 14. Target Anchors

QHO Consideration

- QHO surrogate value
  - Surrogate values for < 0.1% health impact
    - CDF: < 1E-4
    - LERF: < 1E-5
  - NEI 18-04 recommend arbitrary value
    - 5E-7/py to 7500 mSv
    - Associated with high probability of death

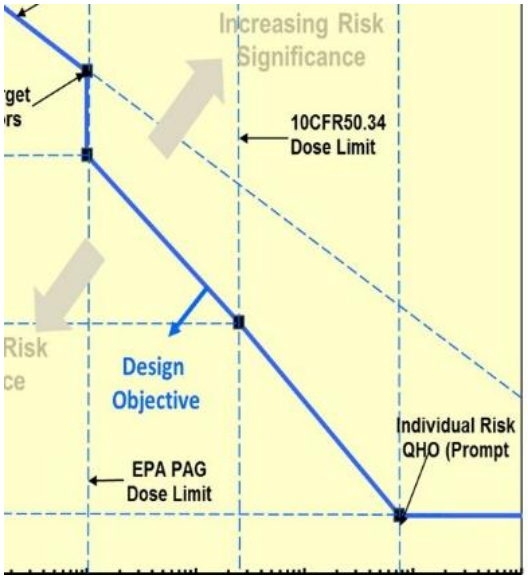


Figure 15. F-C curve

- Relate tolerable cancer risk to radiation dose
  - 0.1% prompt fatality can be a country specific value
  - Dose threshold for prompt fatality have to be determined
  - If maintain interpolated relation & fatality frequency of 5E-7

$$\log D_{0.1\%} = \frac{\log(F_{0.1\%}) - 1.04E^{-2}}{-4.13E^{-4}} \approx \log(\,10000\ mSv)$$

Other Consideration

- Korean specific regulation- Cs-137 safety goal
  - Currently only adopted in Korea, Finland and Canada
  - Designed based on conventional NPP with 1800 MWt core
  - May be contradictory to **technology inclusive approach**
  - Longer assessment duration can partly account for impact

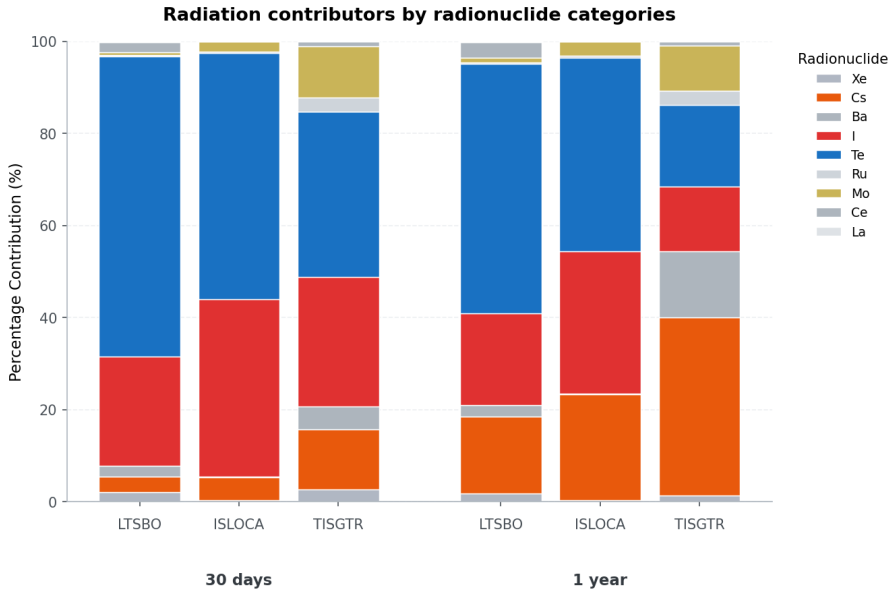


Figure 16. Radionuclide contribution

	Core inventory mass (kg)			
MELCOR RN Class	ABTR (SFR)	PBMR-400 (HTGR)	MSRE (MSR)	Fukushima Daiichi 1
Xe	4.27	65.2	2.85E-04	0.42
Cs	3.71	34.4	0.17	67.0
Ba	1.78	27.9	0.24	28.5
I	0.37	2.13	1.45E-05	0.39
Te	0.60	5.73	-	0.29

Table 3. Partial core inventory of different reactor types

Conclusion

- Implementation of F-C curve will be important
- Insights over the implementation of F-C curve
  - Selection of assessment duration
  - Potential under-representation of certain accident sequences
  - Associated radionuclide contribution
  - Influence of EAB on consequences
- F-C curve relies greatly on national regulation.
- Critical to determine the relevant regulation for anchors.
- Provide insight for future application of F-C curve.

Thank you.