MUPSA Methodology: Future Developments & Safety Goals

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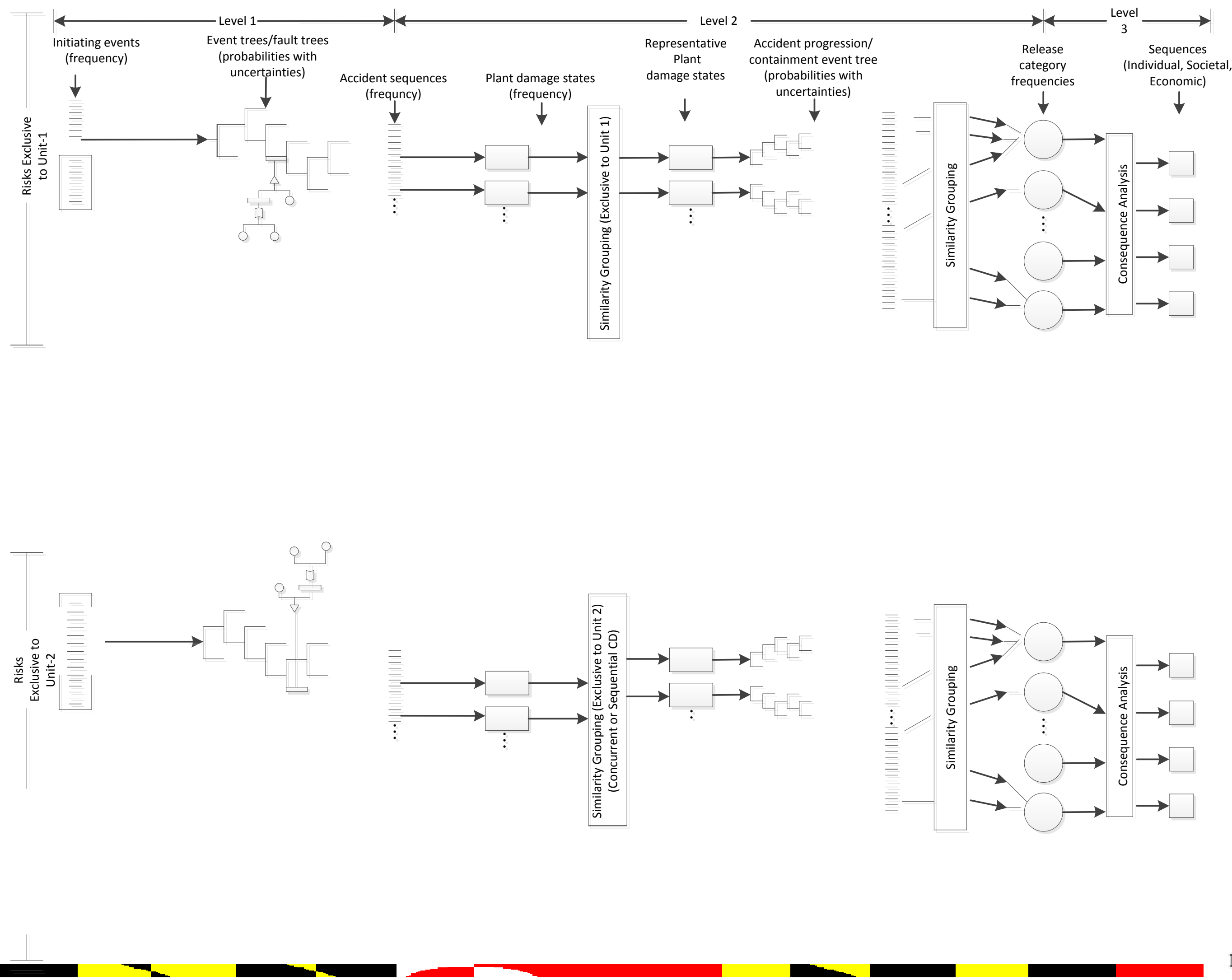
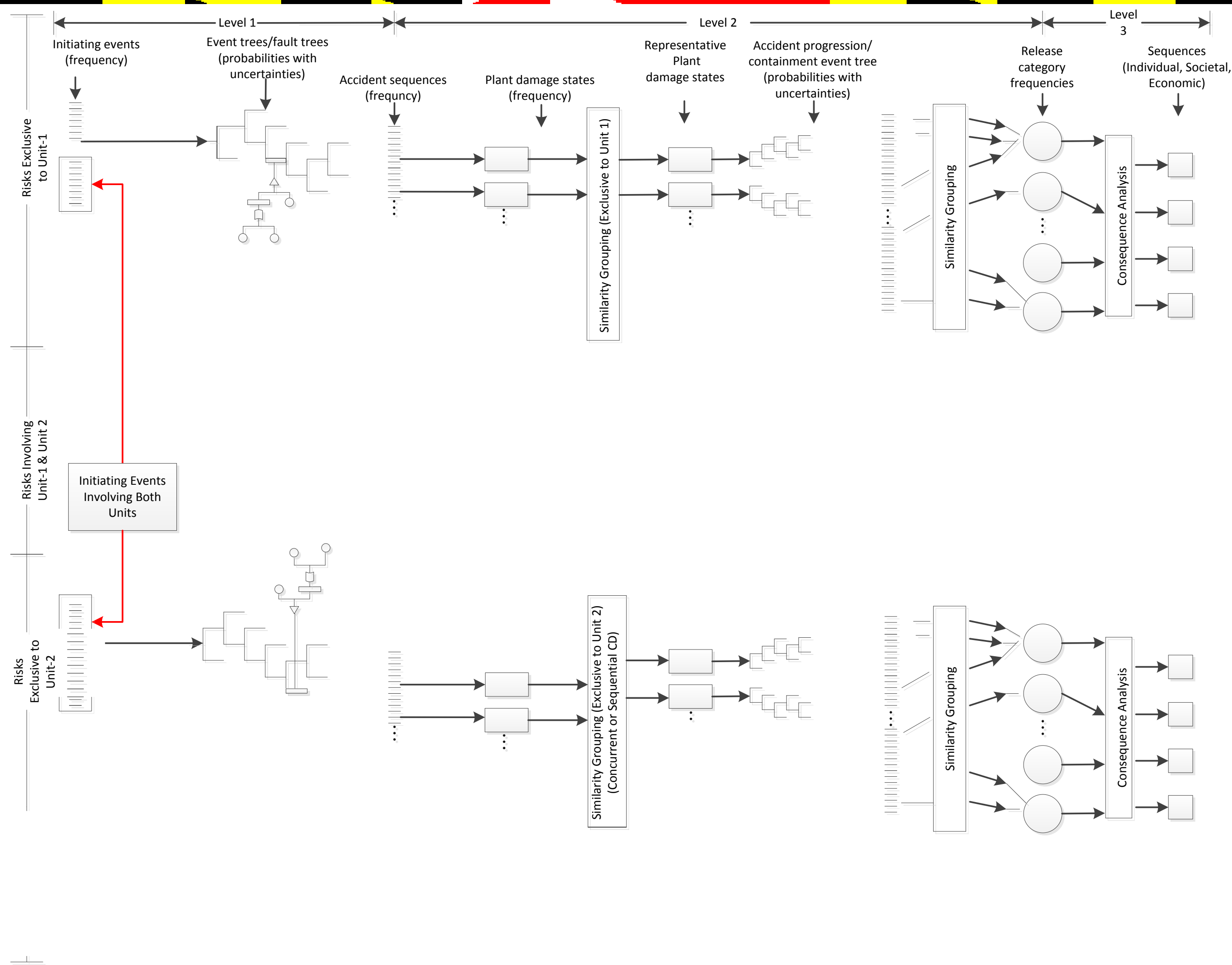
Outline

- Quick Overview of MUPSA Elements
- Review of ”Future Developments” in the contexts of current tools and techniques
- Review of ”Safety Goals” in the Context of Multi-Unit
- Final Observations

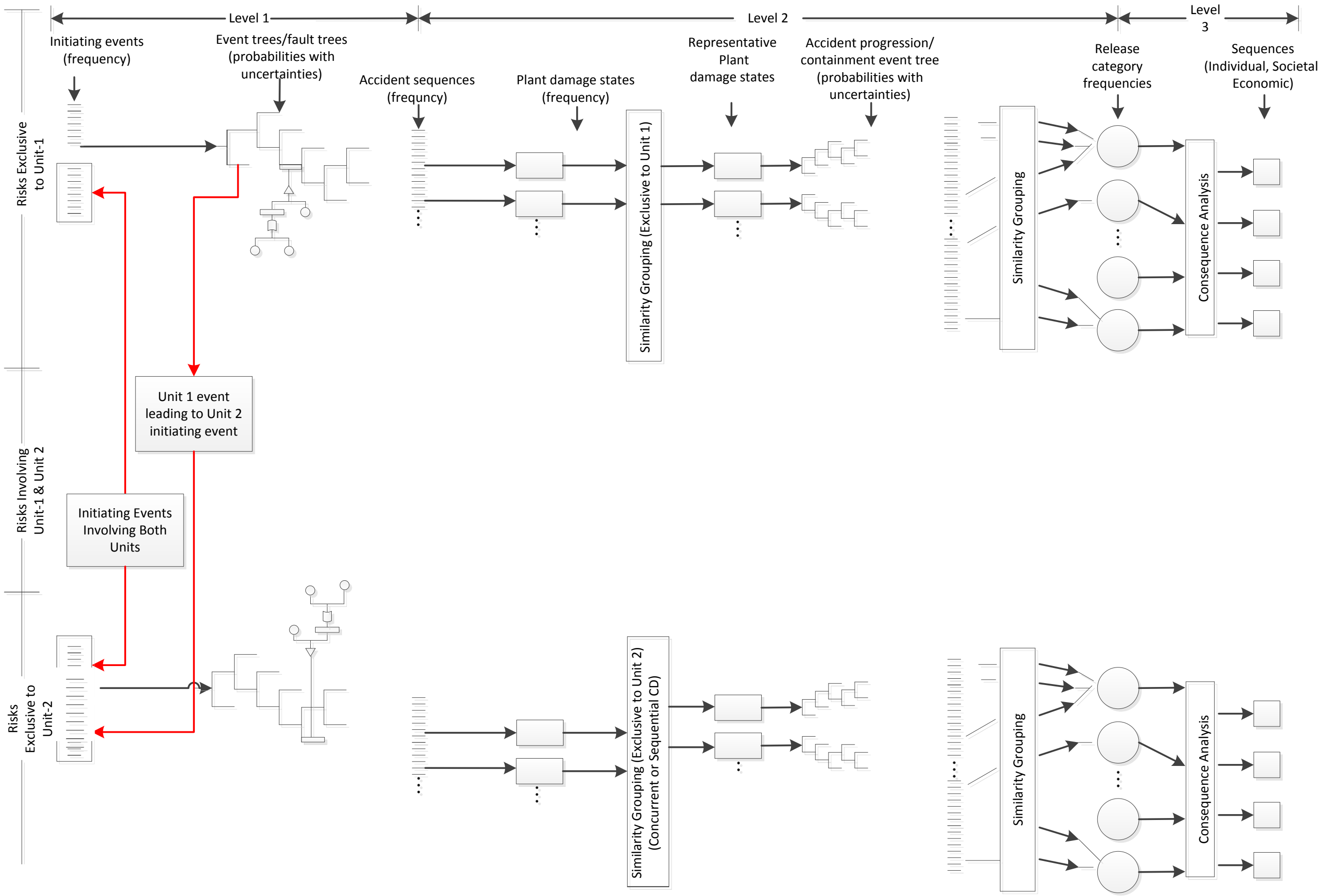
Quick Overview of MUPSA



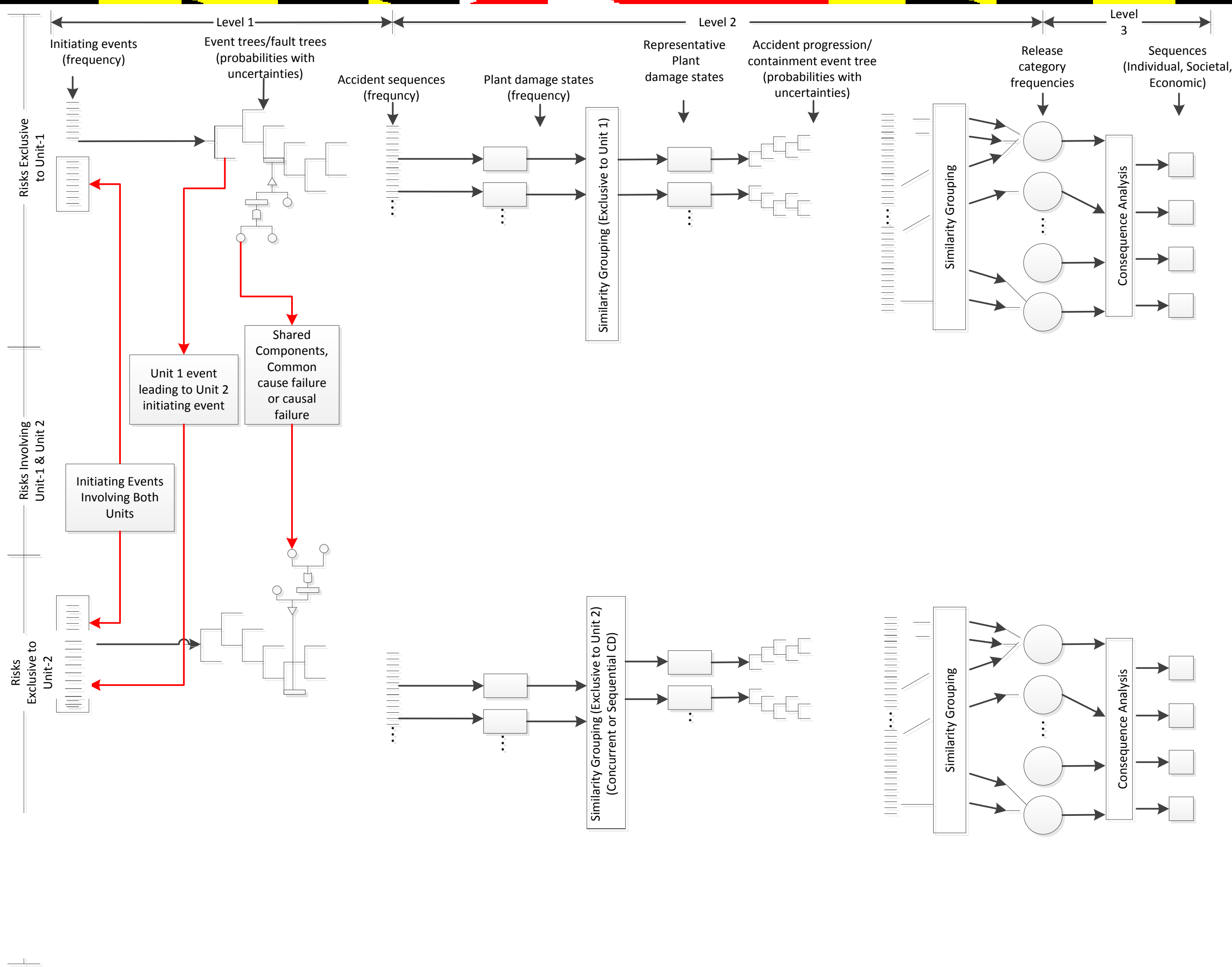
Quick Overview of MUPSA (Cont.)



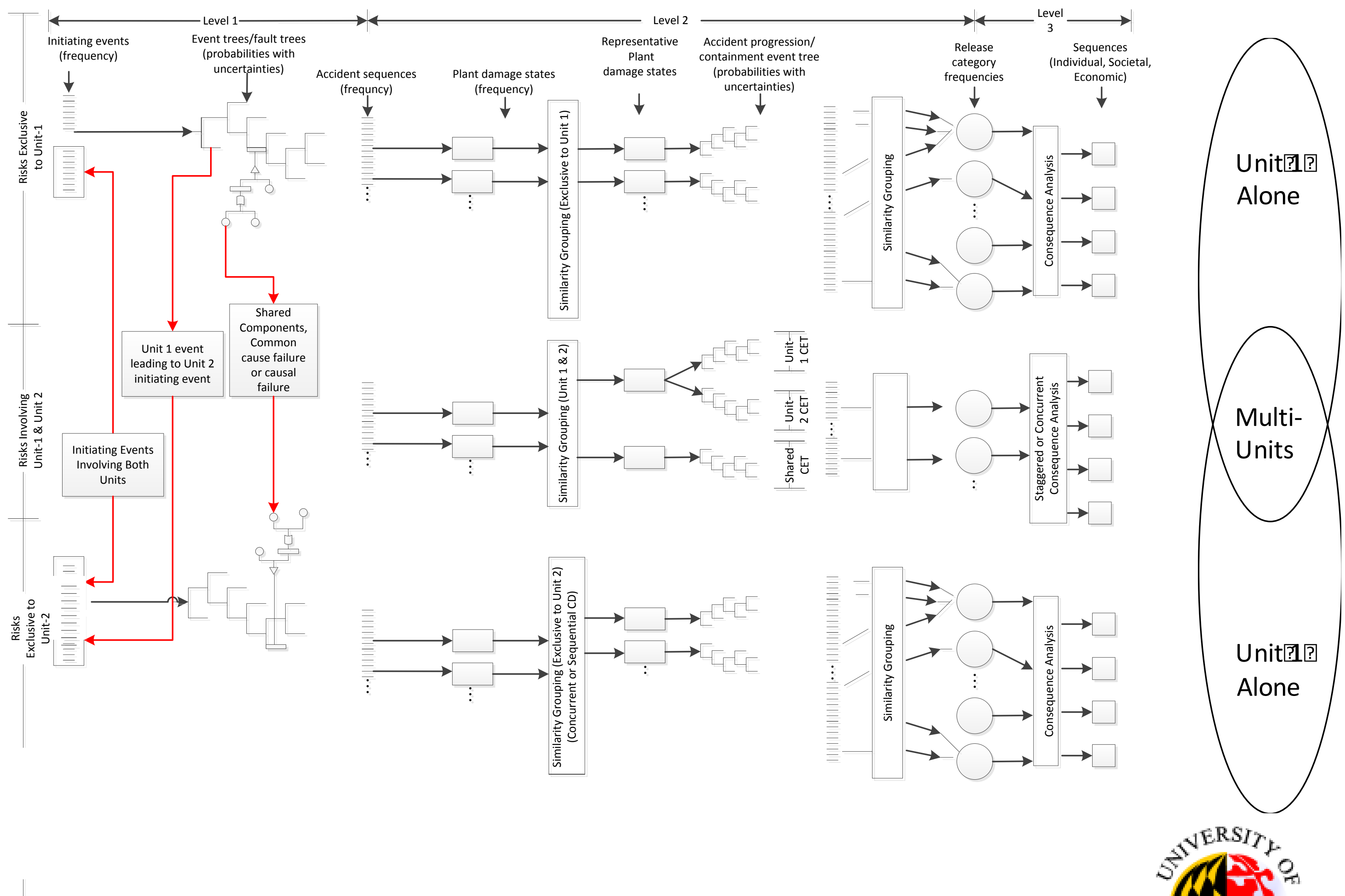
Quick Overview of MUPSA (Cont.)



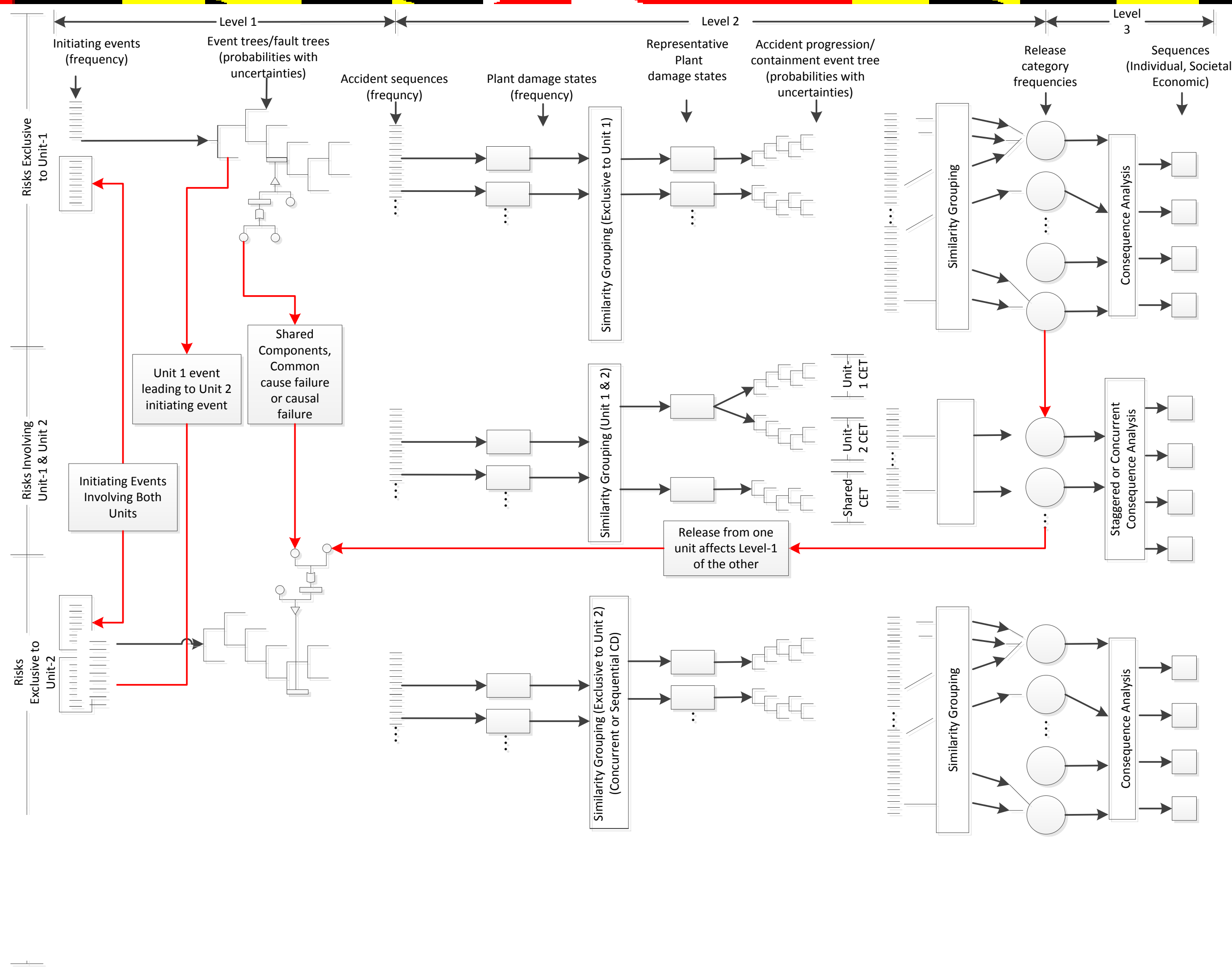
Quick Overview of MUPSA (Cont.)



Quick Overview of MUPSA (Cont.)



Quick Overview of MUPSA (Cont.)



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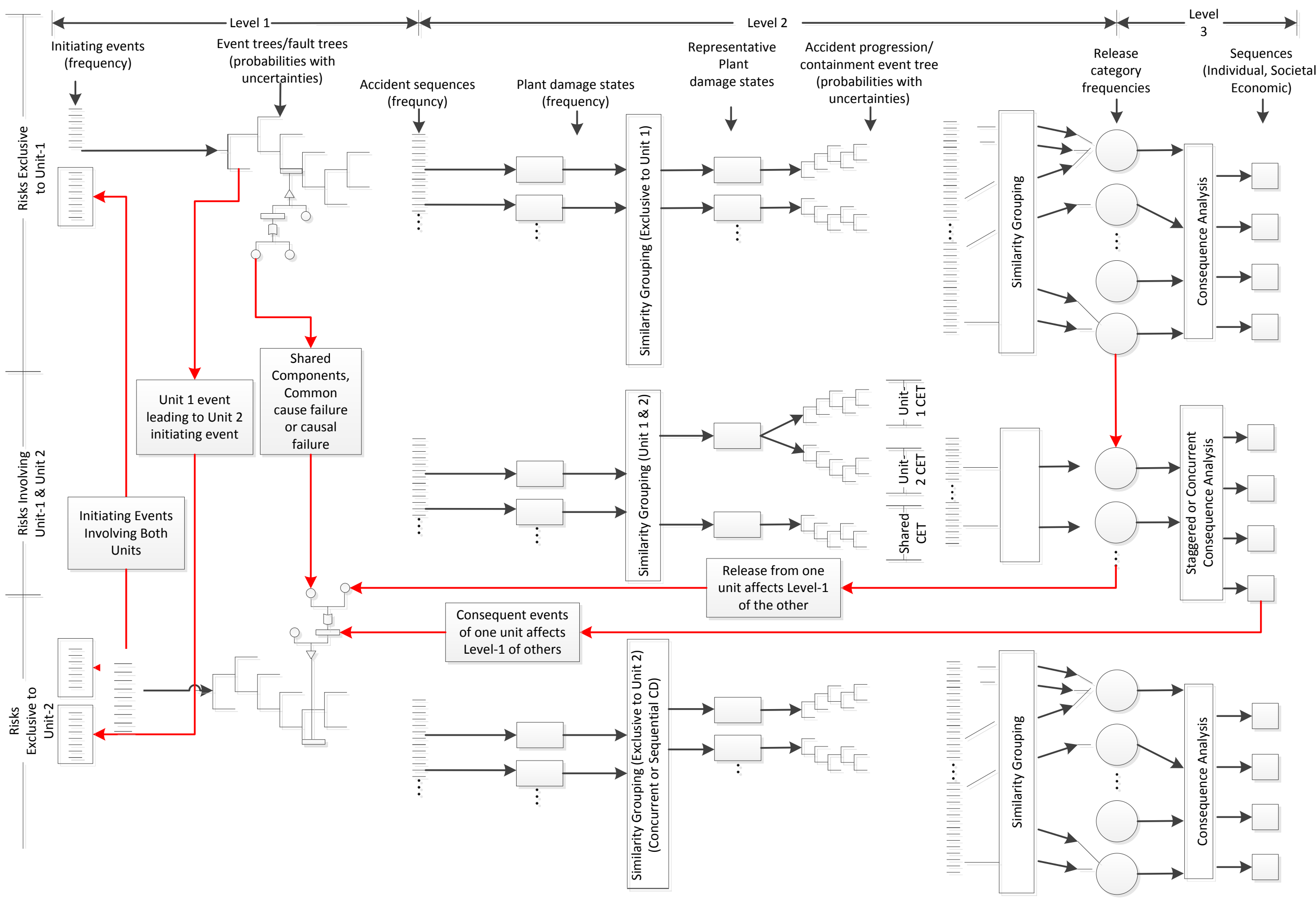
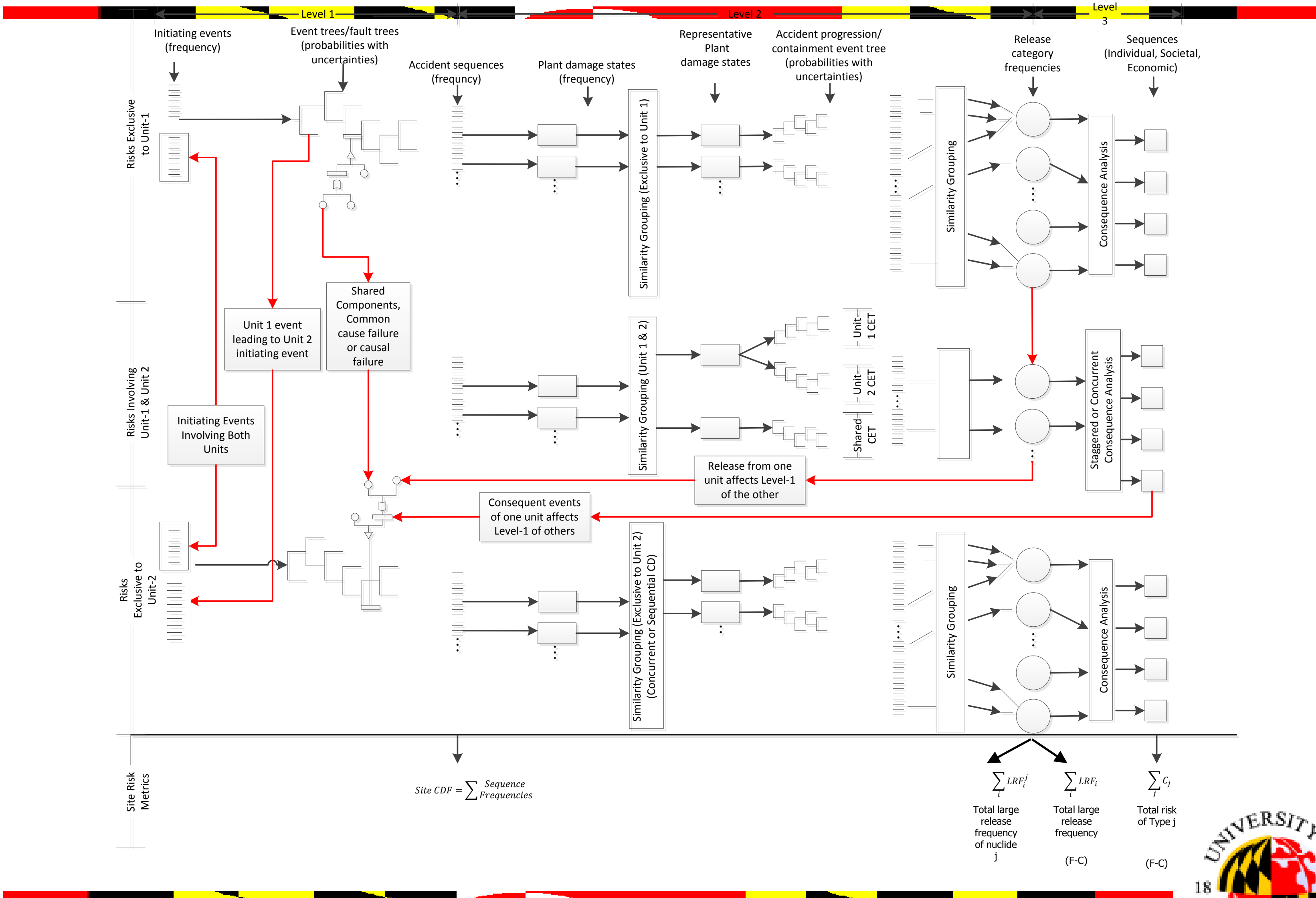


Quick Overview of MUPSA (Cont.)



Future Developments

- This chapter elaborates on key developments for future MUPSAs:
  - Definition and adoption of risk metrics applicable to a multi-unit site involving more than one large-scale radiological sources (such as reactor units and spent fuel storage units). These metrics could be considered as direct measures or surrogates to safety goals. Risk metrics such as the traditional Core Damage Frequency (CDF), Large Release Frequency (LRF)
  - Severe accident models that handle multi-unit accidents are critical for future developments. For example, new site-level plant damage states, release categories that adequately characterize the release characteristics involving more than one radiological source such as the release magnitudes, energies, and timing for units experiencing severe accident, including spent fuel storage and other radiological sources should be developed.

Future Developments (Cont.)

- Extend Level-3 PSAs (for example the U.S. NRC's Vogtle). We need more elaborate models that properly address multiple release sources to evaluate release situations more representative of site-level releases, including multiple intermittent points of release, differences in the timing of release, type and release energies associated with plume rise considerations, evacuation options consideration prior releases, and possibly temporal variations in meteorological conditions in discrete consecutive release situations.
- Consideration of site condition (Level-3) in restricting operator access due prior releases, recovery actions and accident management measures conditioned on the state of other units, as well as severe accident conditions (Level-2) in one unit affecting Level-1 accident sequences and subsequent accident progression of another unit represent backward effects in Level-1, Level-2 and Level-3 MUPSA.
- Better understanding of the site response to seismic and other external events and possible spatial correlation in ground motion and dependencies among SSC fragilities of the reactor units and fuel storage units.

Description of Risk Metrics

- **Level-1 Multi-Unit Metrics**

For site-CDF two possible metrics: 1) Concurrent CDF (C-CSF) representing *frequency of nearly concurrent, CDFs per year* of all or specific permutations of the units on the site (or combinations when units are identical); 2) Site-CDF (S-CDF) expressed as the *frequency of one or more core damage events per year.* Clearly S-CDF combines exclusively single and concurrent CDF events.

Permutation since the order of events and their dependencies in non-identical units would be important.

- **Level-2 Multi-Unit Metrics**

Two Metrics are possible: 1. Frequency of all possible scenarios (or group of scenarios) leading to a large release from one or more radiological source terms on a site per year, referred to as the site large release frequency (S-LRF) .

2. Frequency of a specific release category from core damages of one or more units on a site per year or due to damages of other radiological sources per year, referred to as the site release category frequency (S-RCF)

Concern: what release constitutes as “large”, particularly for discrete releases or nearly concurrent release from the site? Categories of releases and their frequency per year for identified multi-unit sequences in terms of the nature, timing, and magnitude of the release are presently ill defined.

Description of Risk Metrics (Cont.)

- **Level-3 Multi-Unit Metric**

➢ The consequences are often in form of prompt fatality, long-term health effects, fatalities, property damage and other economic losses.

- Site frequency-consequence (S-FC) risk profile curve, expressed as the exceedance frequency of a specific consequence per year for the total aggregated risk for the site or for a particular release category defined in Level-2.
- Site quantitative health objectives (S-QHO), which describe the total mean frequency of specific safety health objectives such as the prompt fatality and long-term health effects fatalities per year due to the total aggregated risk from all release categories of multi-unit accidents identified in Level-2 analysis.
- Site release category-specific QHO (C-QHO), which describe the total mean frequency of specific health objectives per year due to a given type or class of release such as the prompt and long-term health effects per year due to a specific release category associated with a multi-unit accident in Level-2 analysis

➢ If risk aggregation over all site-level initiating events not intended, risk metrics can be expressed for specific initiating events or hazards, (e.g., seismic alone)

Further Clarifications and Developments Needed

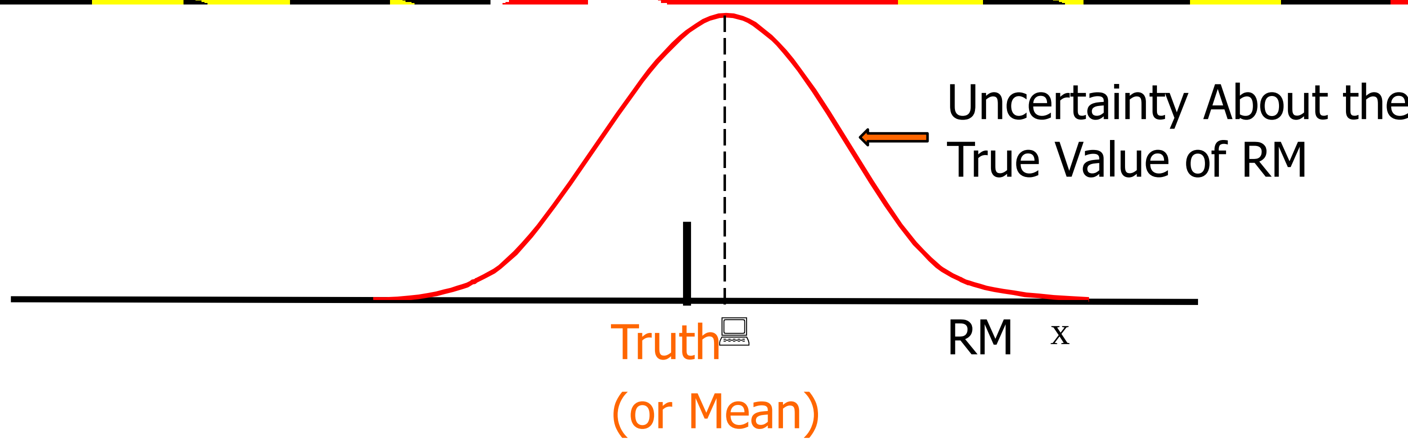
What is considered as large release?

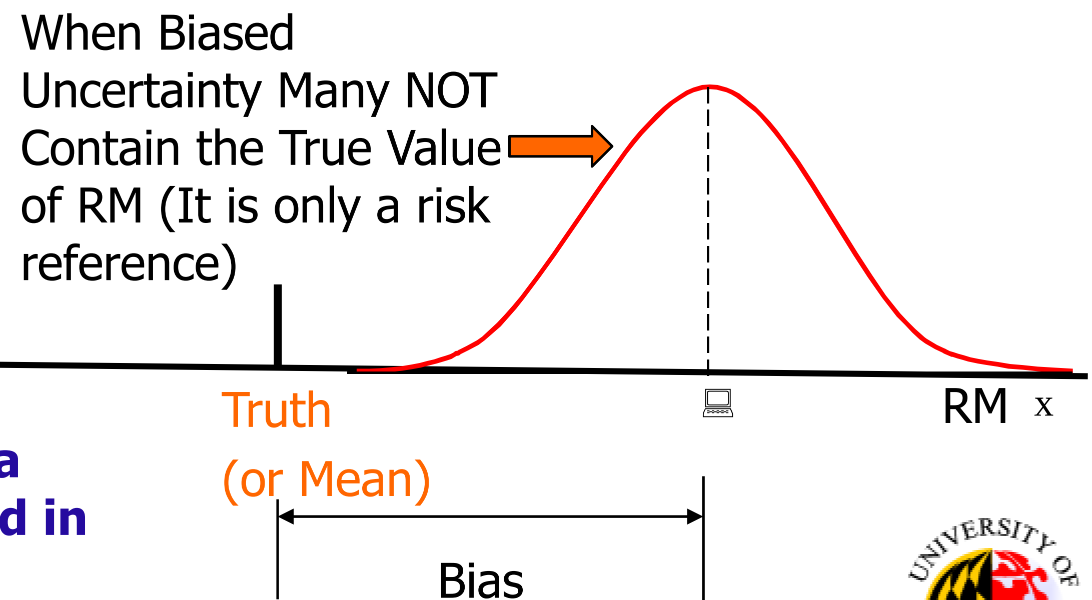
1. Number of resulting prompt fatalities: (NUREG/CR-6094 considers a large release as one that leads to a prompt fatality for an individual standing one-mile from the site,
2. Amount of radionuclide release: a) Absolute measure deterministically prescribes the dose considered as large using isotopes that highly contribute to offsite health effects, such as I-131 and Cs-137; b) Relative measure express fractional release of core inventory of the same or radionuclide groups considered (NUREG/CR-6595 (Appendix deems a large release when 2-3% of the I-131 inventory as large). Both options are useful for application to multi-unit.
3. State and integrity of the site reactor pressure boundaries, containments and spent fuel pool at the time of release. For example: failure of two RPVs and subsequent loss of containment pressure boundaries due to bypass in one unit, and structural damage of the other unit within a few hours of core melting and fission product release from fuel during which opportunities for attenuation of the airborne concentration are minimal.

Further Clarifications and Developments Needed (Cont.)

- Approached for Risk Aggregation is needed: the process of combining the amount of exposure, consequence, likelihood or frequency of various risk metrics into a single metric for comparison to safety goals or for estimating the overall risk and propose accident management strategies. Probabilistically the combined metric might be similar metrics: S-CDF, or dissimilar metrics: a CDF and spent fuel damage frequency.
- The most important reason for aggregation is to combine risks from multi-units, multi-source, multi-hazards, and multi-phases and show conformance to safety goals or other design objectives or requirements.
- Even when dealing with vastly different levels of uncertainties about a risk metric (e.g. CD from internal and external events) we still can aggregate if there is no bias.
- If we have introduced "bias" in the true or mean value of a RM, it should be corrected before aggregation
- Bias in RMs is introduced by: Conservatisms, Approximations, Scope Limitation, Simplifications, Team Experience / Level of Quality Controls / Adherence to Standards, Unconventional PSA Method
- Bias is not uncertainty!
- It is possible way to assess amount of bias is by expert elicitation

Uncertainty vs. Bias



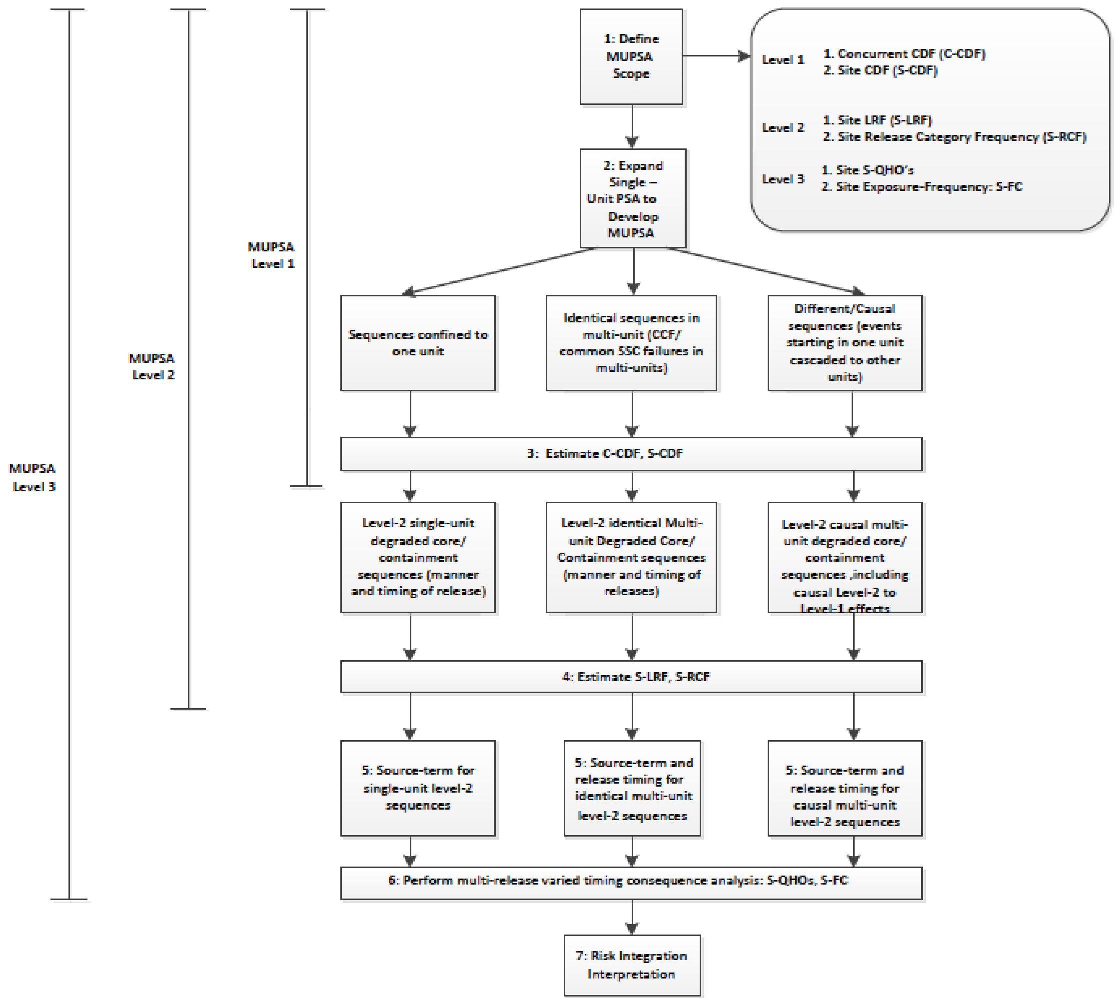


- **Quantification methods via expert elicitation discussed in the last meeting**

Other Future Developments that need Research (NOT DISCUSSED IN THE RESPORT)

- Dependency modeling between multi-units: Common cause failures of hardware and human failure events
- Intra- and inter-unit fragility dependencies
- Ground response dependency models
- Role of organizational events
- Better tools to handle very large scale models
- Proper modeling of FLEX equipment
- Models of site accessibility and effects on HRA

MUPSA Level-1, Leve-2, and Level-3 Sequences and Risk Metrics



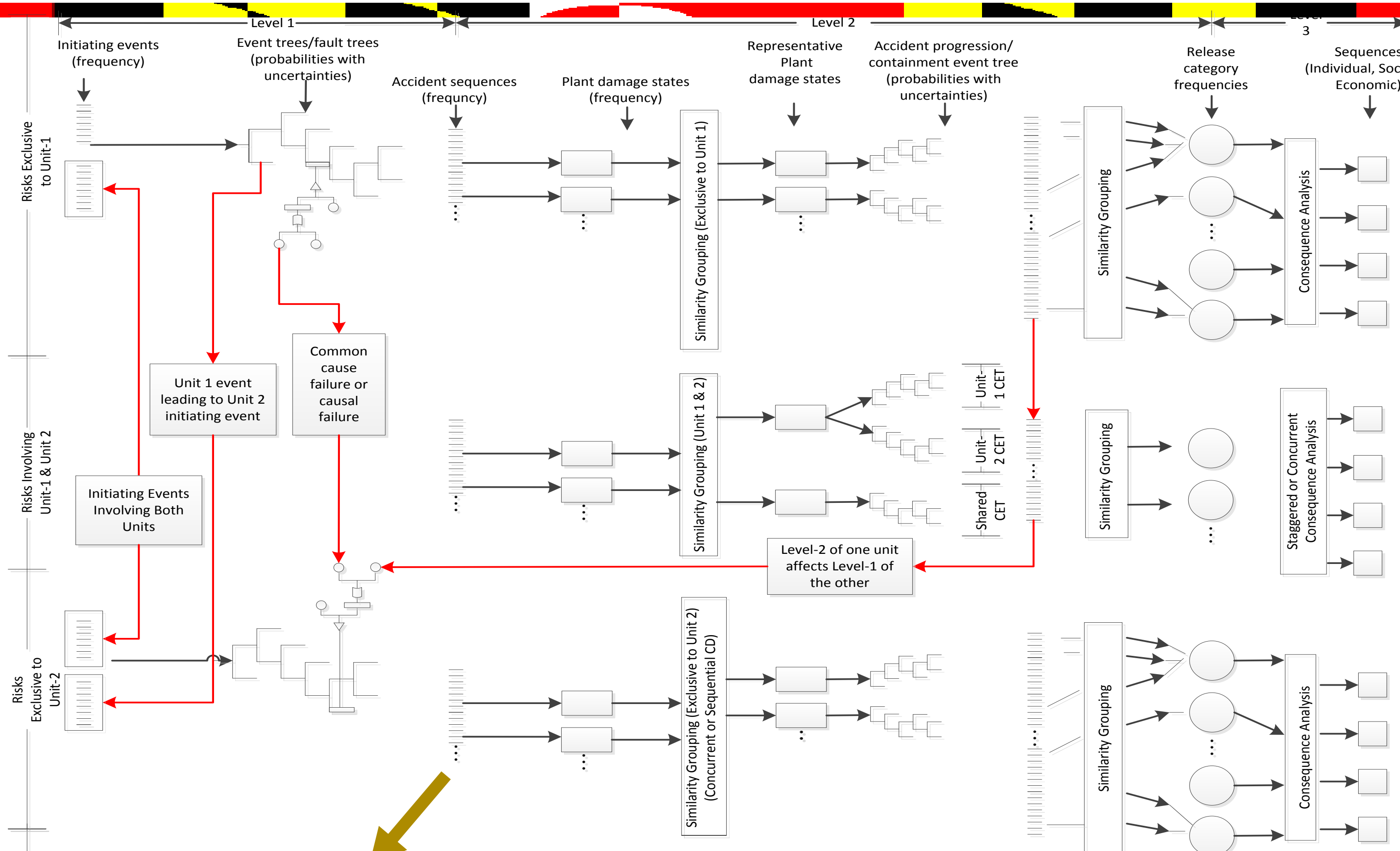
Safety Goals

- Safety goals are often needed to demonstrate and communicate safety of nuclear power plants. They are mostly developed in a hierarchical framework, with the highest-level representing qualitative goals consistent with legislative and other broad societal needs, and the lower levels of the hierarchy reflecting more quantitative objectives, surrogate risk metrics, and sometimes design and operating performance objectives in line with the high-level qualitative safety goals.
- The safety goals could address health and safety objectives, also they may be expressed in economic terms, reflecting monetized aversion of any environmental and societal impacts, such as land contamination and population displacement. These goals may be applicable to a nuclear unit (such as a reactor) or a site.
- The conformance is often in form of establishing risk acceptance levels (or target levels) in form of quantitative objectives, such as the frequency of prompt fatality or their surrogates such core damage frequency (CDF) or large release frequency (LRF) estimated by performing PSAs.

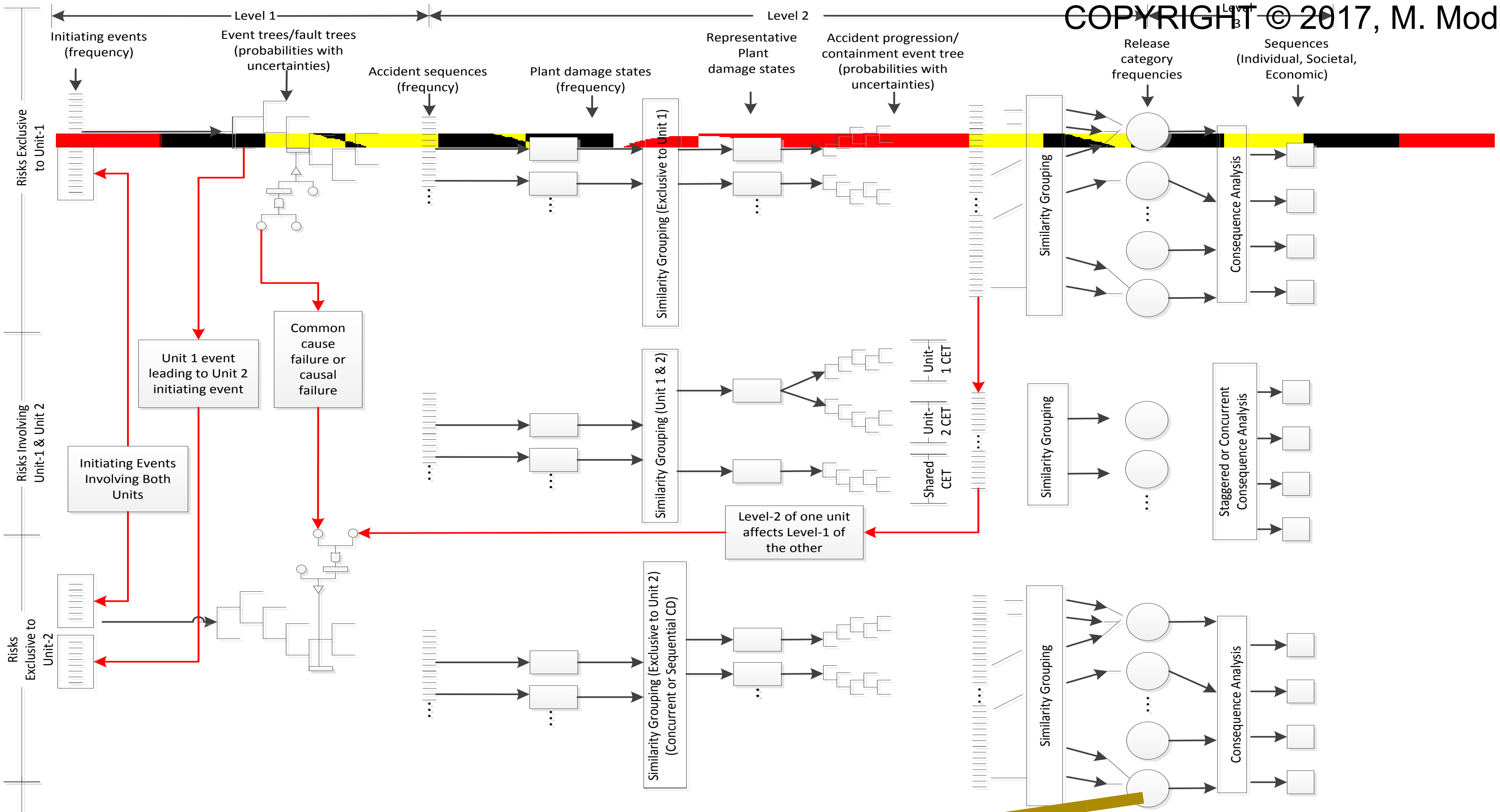
Safety Goals (Cont.)

- Increased attention paid to societal disruption following the Fukushima Daiichi accident. While there is a common lack of societal disruptions goals, this could lead to new multi-unit safety goals where it sets societal disruption limits, for example in form of monetized metrics. However, at this point no consensus on which metrics are relevant exist
- Two most important points of view of safety goals that are applicable to an entire site are related to the site risks that subject individual or group of people to radiological harms. Examples of these goals applied to a site are the U.S. safety goals, where acceptable levels of individual prompt fatality and population (referred to societal) long-term cancer fatalities are designated. These types of goals are also expressed in form of the maximum frequency or probability for a given type and amount of radioactive exposure from the site to an individual or population that might correspond to an undesirable outcome such as prompt fatality or cancer death.
- The IAEA has been developing a framework to support selection of appropriate safety goals for its member states. This framework will offer an ideal opportunity to develop an international consensus

Safety Goals (Cont.)



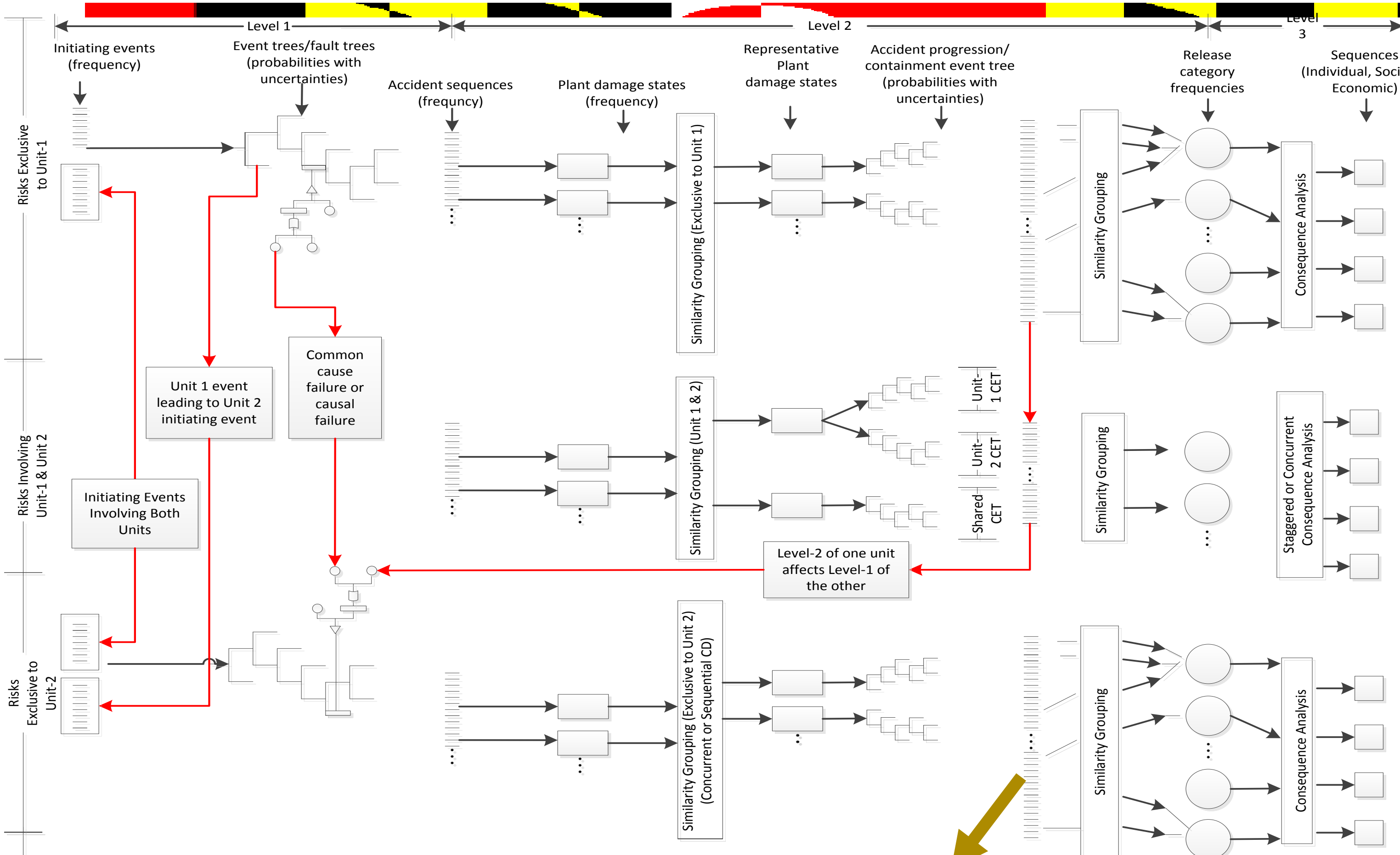
Frequency Limits: Many countries have single-unit CDF limits of 10-4/Reactor-year for operating plants, and 10-5/Reactor-year for new plants. This includes U.S., Japan, Canada, Czech Republic, Finland, Korea, Russia, and Sweden. Similar new limits for multi-unit sites in terms of S-CDF would be needed (for example 10-5/Reactor-year for existing sites and 10-6/Reactor-year for new sites are possible options).



Limits of LRF for a whole site consisting of multiple units. It is conceivable to maintain that the range of 1x10-6 to 5x10-7 /year limit to multi-unit sites. Note, in addition to single unit large releases risk of concurrent releases, albeit with lower frequency, are conceivable.

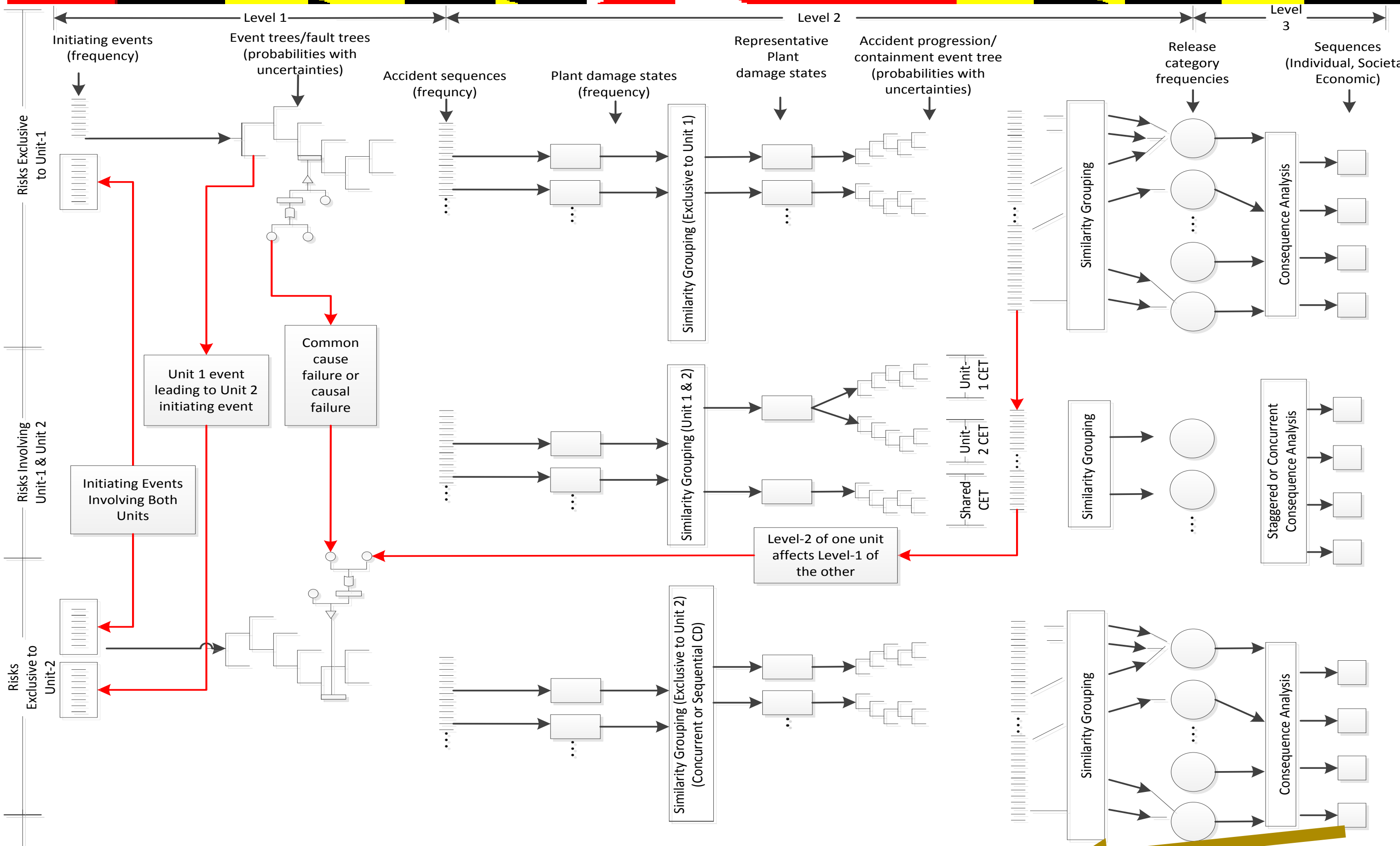
Frequency limits for particular class of MU releases are also possible. For example, limit the frequency of radiological releases from accidents in one unit that compromise the integrity of a shared containment for other units.

Safety Goals (Cont.)



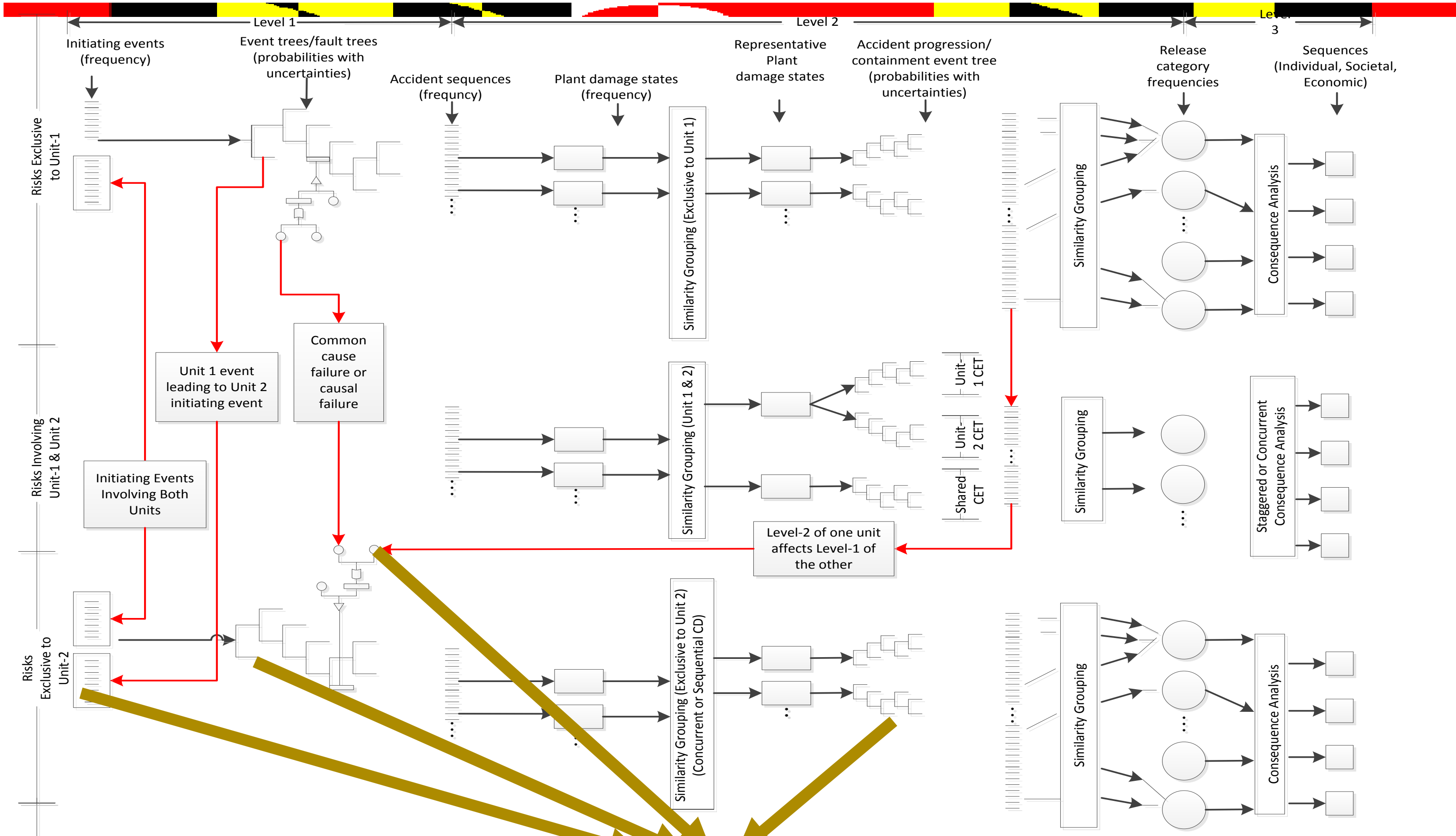
Exposure Limits: Some countries have proposed this kind of limit. For example, existing Canadian (single-unit basis) limits of Small Release Frequency (SRF) of > 10^{15} Becquerel of ^{131}I < 10^{-4} /Year; and LRF of > 10^{14} Becquerel of ^{137}Cs <10^{-5} /Year. Examples of using relative limits such as 1 % of the core inventory of ^{137}Cs have also been proposed.

Safety Goals (Cont.)



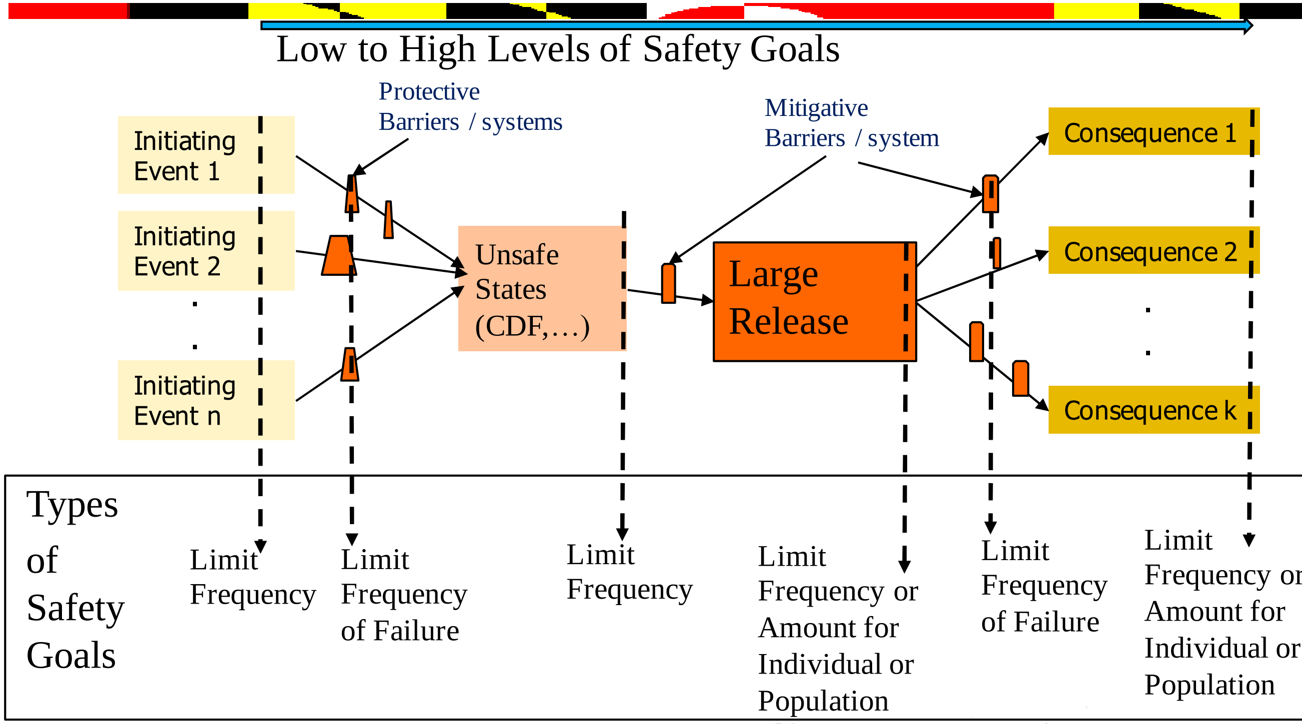
Consequence Limit: For example, the U.S. safety goals policy statement that sets individual prompt fatality limit and long-term population (societal) cancer fatalities

Safety Goals (Cont.)

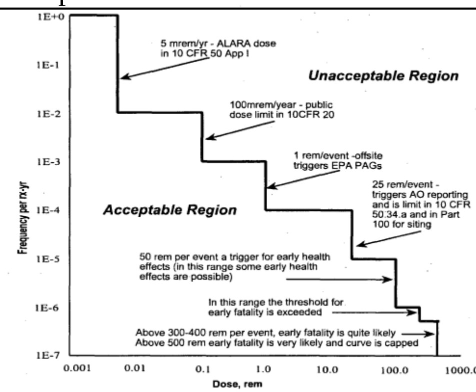


Performance Levels: For example, acceptable probability of failure of the reactivity control or reactor protection system. Or NRC Severe Accident Policy Statement limits conditional containment failure probability (CCFP) < 0.1. The safety criterion for new or advanced plants by the NRC sets a target for CCFP< 0.1.

Safety Goals (Cont.)



Combination: For example, maximum frequency versus exposure or consequence is established. Consider consequences, c, (e.g., in terms of cost) of a release sequence with frequency, f. An example of this approach is the proposed technology neutral licensing adopted in NUREG-1860 for licensing future nuclear plans



Safety Goals (Cont.)

Beside the U.S. only France has announced quantitative safety goal for its nuclear power plants. It has required that the probability of cancer due to all causes for radiological exposure not to exceed 10^{-6} per reactor per year

Far more efforts and definitions are needed to implement and use safety goals in the context of multi-unit sites

Thank you for your Comments and Attention!

Some of the Key Conclusions of MUPSA Ottawa Workshop

- Site-based risk metrics are needed to augment reactor-based risk metrics
- Level 3 MUPSAs are important and should consider all sources, timing and modes of release
- Multi-unit risk should be used for identifying important site risk contributors
- Multi-unit risk insights can be used to enhance the implementation of DiD principles and to show whether current regulatory requirements are adequate
- Better understanding of inter- and intra- unit dependency modeling is needed
- Societal disruption as an important safety goal parameter was discussed (no consensus reached, some felt PSAs may not be an appropriate tool for this goal)

BACKUP ON AGGREGATION

Estimation of Bias by Expert Elicitation

- Similar to estimating unknown events, bias may be treated as a random variable to be estimated by multiple expert aggregation
- Bias may be treated as a multiplicative error factor, F, that corrects the uncertainty distribution's scale
- For example, F may described by the lognormal distribution

$$\frac{P(RM_i^t)}{P(RM_i^e)} = F_i; \;\; F_i \sim LN(b_i, s_i)$$

Estimation of Bias by Expert Elicitation (Cont.)

Likelihood of n equally capable expert bias estimations, F_i :

$$L(F_i|b_i,s_i) = \prod_{k=1}^{n} \frac{1}{\sqrt{2\pi}} \frac{1}{F_i^k s_i} e^{-\frac{\left[\ln\left(F_i^k\right)-b_i\right]^2}{2s_i^2}}$$

Clemen and Winkle[1] propose adjustments to include credibility weights of each expert, $w_{i,}$ ranging from 0 (not credible) to 1 (fully credible).

$$L(F_i|b_i,s_i) = \frac{1}{\tau} \prod_{k=1}^{n} \frac{1}{\sqrt{2\pi}} \frac{1}{F_i^k s_i} e^{-\frac{\left[\left(ln\left(F_i^k\right)\right)^{w_i}-b_i\right]^2}{2s_i^2}}$$

Normalization factor τ should be computed based on the values of w_i to preserve the characteristic of L(.) as a probability

[1] "Combining Probability Distributions from Experts in Risk Analysis, Robert T. Clemen and Robert L. Winkler, *Risk Analysis, Vol. 19, No. 2, 1999"*

Estimation of Bias by Expert Elicitation (Cont.)

$$\pi_1\left(b_i, s_i \middle| \, all \; F_i^k\right) = \frac{L(F_i|b_i, s_i)\pi_0(b_i, s_i)}{\iint_{b_i, s_i} L(F_i|b_i, s_i)\pi_0(b_i, s_i) db_i ds_i}$$

where $\pi_1(.)$ is the posterior and $\pi_0(.)$ is the prior joint distributions of the parameters of the lognormal distribution of F

Once the posterior values of b_i, s_i are known, then the true probability distribution function of values of the risk metric of interest would be

$$P(RM_i^t) = F_i \times P(RM_i^e).$$