EPRI HEAF with Aluminum

Industry Survey and Analysis Results

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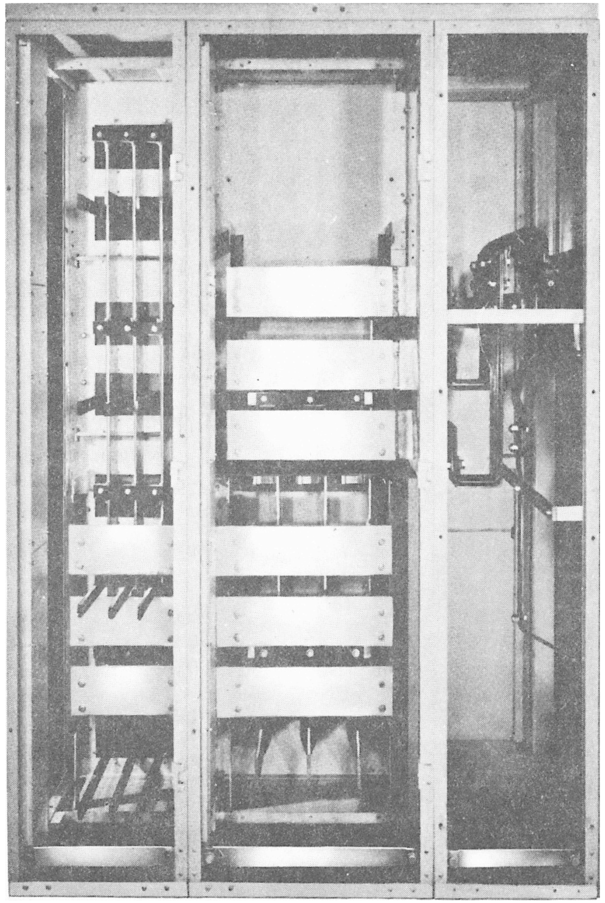
Important Context For EPRI Analysis and Insights

- The EPRI assessment does not calculate the actual unit-specific Fire PRA risk
  - No actual plant models were collected by EPRI or used in EPRI's analysis
  - Limited Fire PRA data along with intentionally bounding and conservative assumptions were used for the sensitivities
- EPRI work does NOT conclude "more analysis was needed" for some plants due to large increase of risk due to Aluminum
  - Without actual ZOIs and information about location of nearby targets, it is NOT possible to determine a delta risk
  - It is known that even for the plants that did not "screen out" the EPRI analysis is HIGHLY conservative and, in many cases, known to be unrealistic (i.e., an event of the magnitude postulated cannot physically happen)

HEAF Survey Data Collected for each Plant (95 plants)

- Aluminum usage in the electrical equipment susceptible to HEAFs
  - Iso-phase bus ducts (IPBD)
  - Non-segregated bus ducts (NSBD)
  - Medium voltage (MV) switchgear (SWGR)
  - Low voltage (LV) SWGR / (load centers)
- Electrical design
  - Backup protection Fault Clearing Time (FCT)
- Fire PRA data
  - Existing HEAF scenario information
    - HEAF Conditional Core Damage Probability (CCDP)
    - Full Room Burn CCDP (bounds any increase)

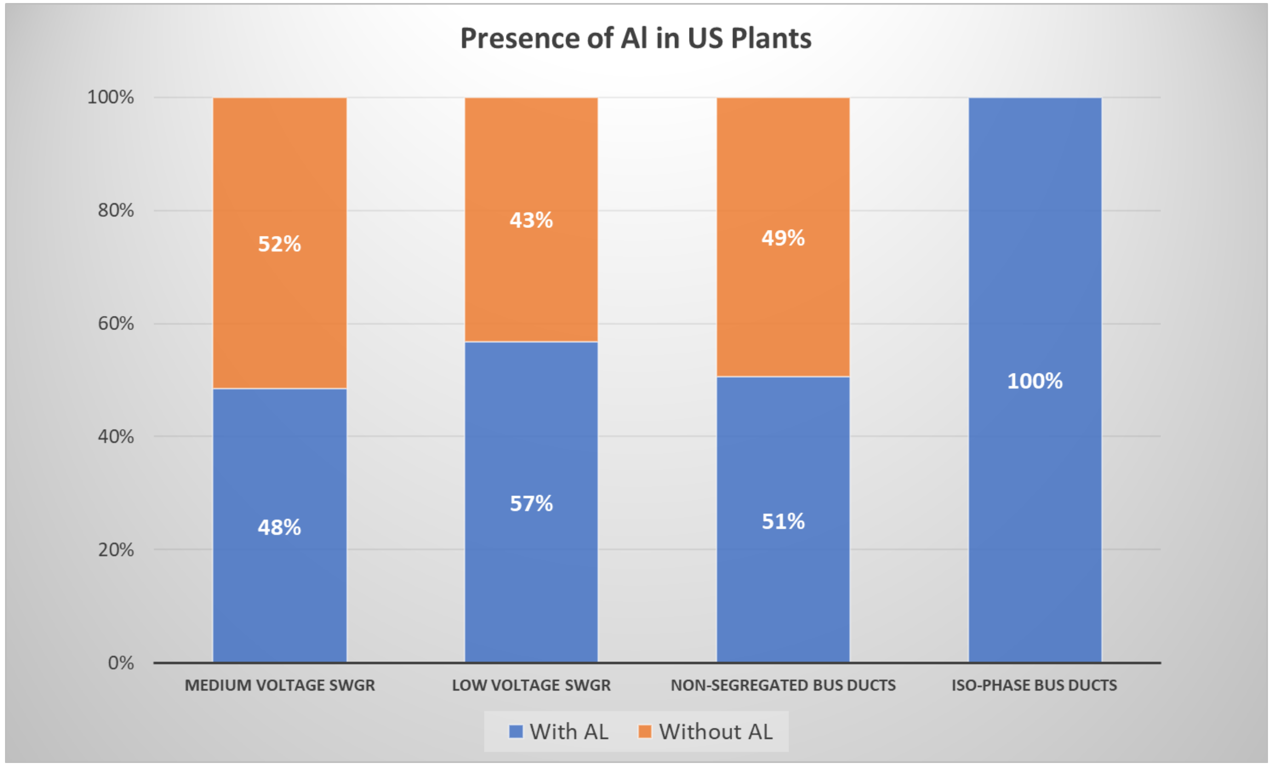


High Level HEAF Survey Results

Insights related to Testing

Summary of the HEAF Survey Responses

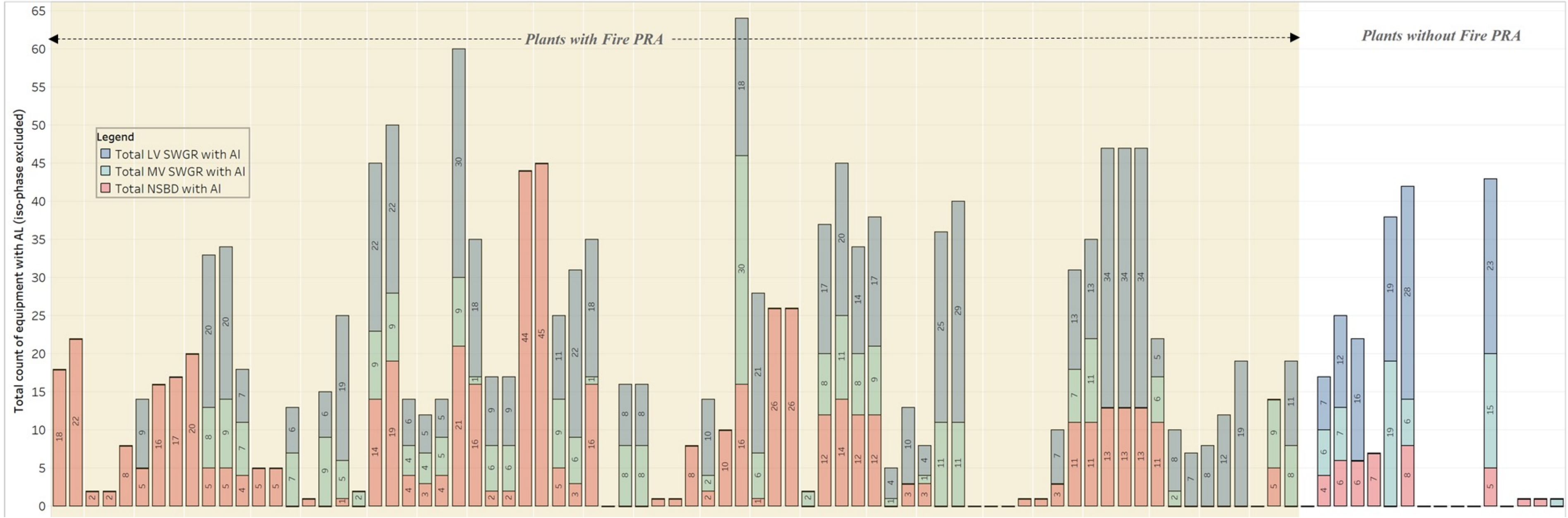
- Survey results and initial insights
  - Responses received from 100% of plants
  - Follow-up and clarification of responses completed
  - 78% of plants provided Fire PRA data
  - 22% do not have Fire PRAs sufficient to provide data



Percentage of Al is higher than initial voluntary response.
Presence of Al is not directly related to increased risk

Aluminum has always existed in the US fleet

- 100% of iso-phase bus ducts are made of Aluminum
- 87% of plants have Aluminum in MV SWGR, LV SWGR, and/or non-segregated bus ducts



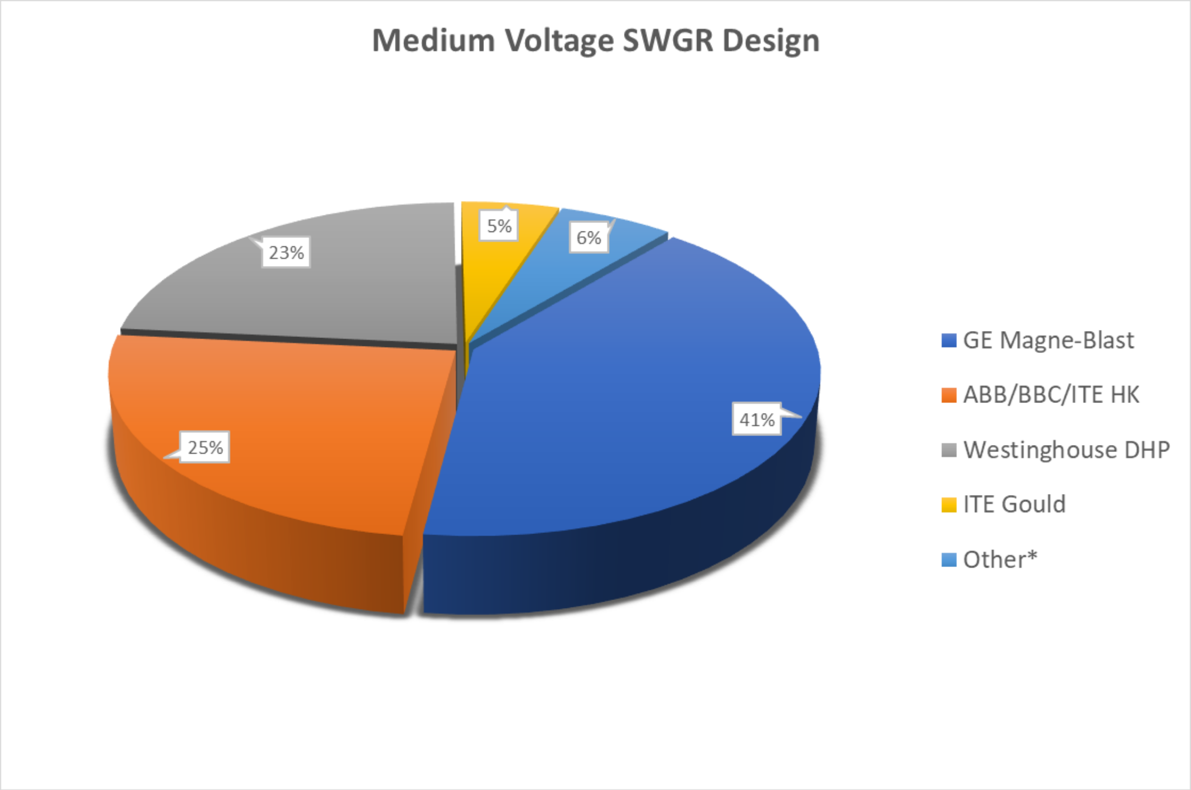
- Putting OE in context
  - Although HEAF events are relatively rare, the US OE does include operating experience, including HEAFs, involving Aluminum

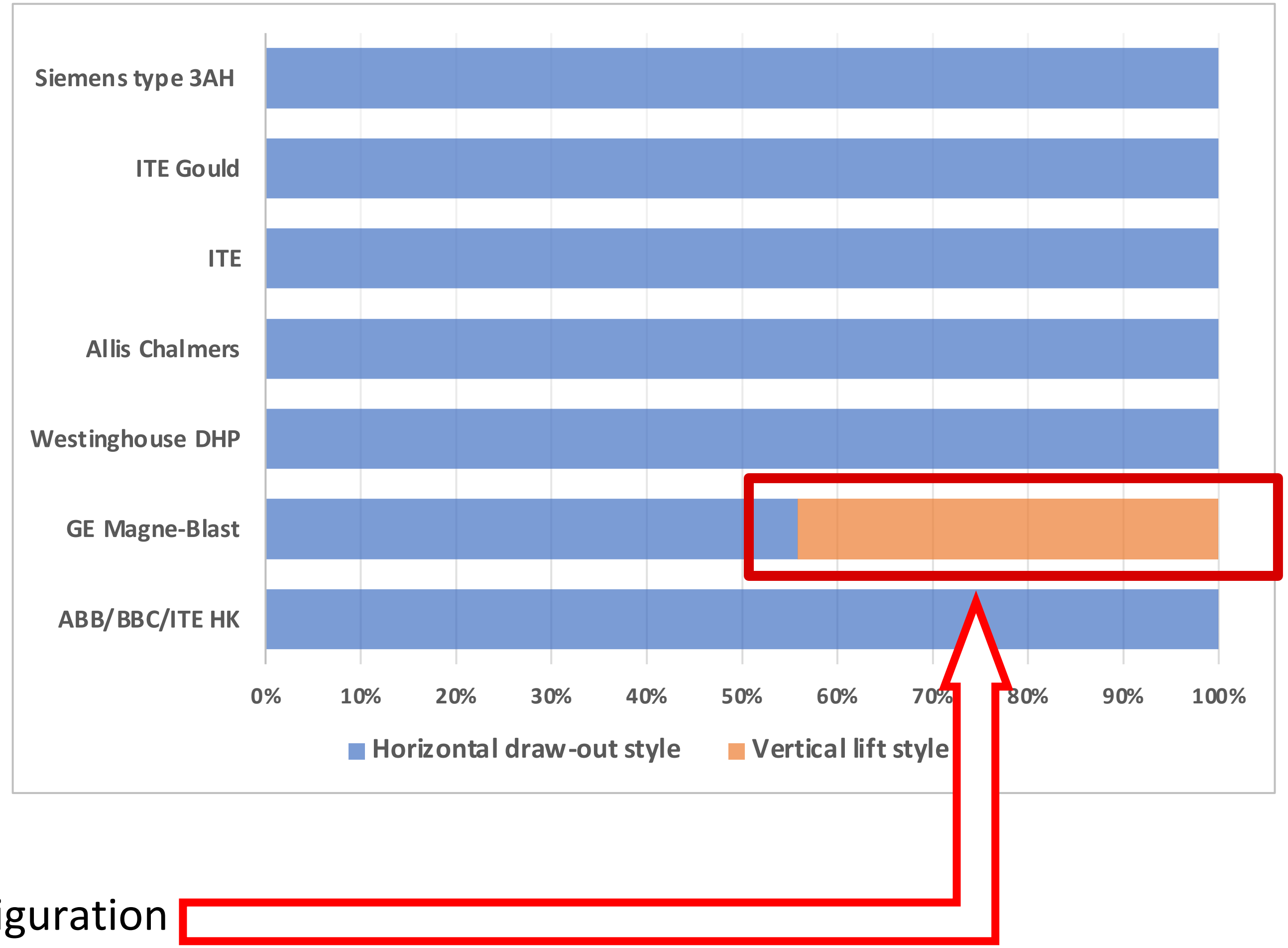
	NSBD	MV SWGR	LV SWGR	ISBD
Estimate of **Component Years** in US Fleet for Eq type WITH AL	24289	12186	34273	11140

EPRI Insights from HEAF-Al Survey Responses

- Medium Voltage Switchgear (MV SWGR)
- Low Voltage Switchgear (LV SWGR) / Load Centers
- Iso-Phase Bus Ducts (ISBDs)

Insights for Medium Voltage (MV) Switchgear (SWGR) with Aluminum



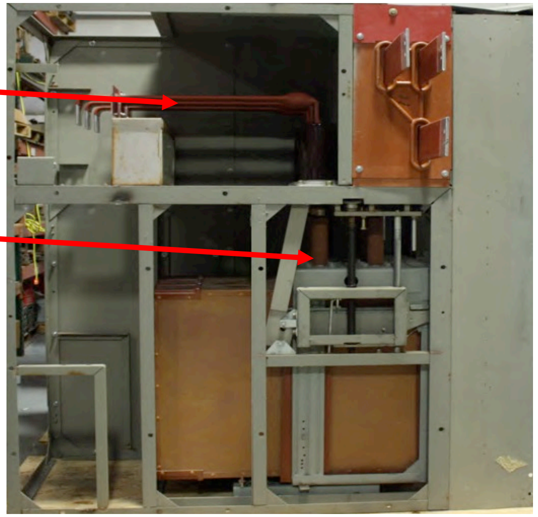


- NRC-RES has only tested GE Magne-Blast vertical lift configuration
- However, >80% of the MV SWGR with Aluminum in the plants are horizontal draw-out style

MV SWGR testing on vertical lift style switchgear is not representative of the majority of plant configurations

Insights for MV SWGR with Aluminum

- For >95% of MV SWGR containing aluminum, it is located in
  - Main bus bars,
  - Primary compartment bus bars, or
  - Both main bus bars and primary compartment bus bars
- NRC-RES Phase 2 testing involved configurations where fault was initiated at the primary compartment bus bars
- US operating experience (OE) shows almost all MV SWGR HEAFs occurred at breaker stabs
  - Only one HEAF event occurred at the primary compartment bus bars
  - Only one "event," and arc blast (not a HEAF) occurred at main bus bar^ location
  - OE also shows two generator fed HEAF events initiated at the copper breaker stabs.
    These events show no evidence that the arc propagated to the aluminum bus bars.

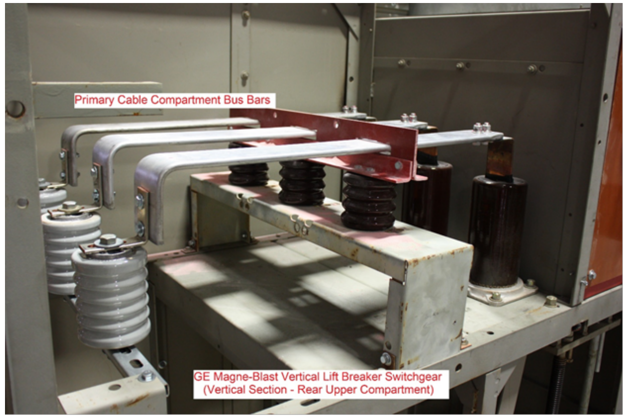


^ International OE - The Onagawa HEAF event did involved the main bus bars.
Onagawa equipment was the vertical lift configuration that represents <20% of the MV SWGR in US plants.

MG SWGR testing with fault initiation at bus bars does not represent the majority of OE where faults initiate at the beaker stabs

Insights for MV SWGR with Aluminum

- > 85% of MV SWGR bus work in the plants is insulated
  - OE suggests HEAF events have occurred in insulated MV SWGR bus work,
  - However, this was when bus insulation was compromised (e.g., aged, cracked w/moisture intrusion)
- NRC-RES Phase 2 testing only tested configurations with uninsulated bus bars
- Large majority MV SWGR configurations include insulated bus bars
- Industry guidance regarding monitoring for insulation damage (EPRI 3002015459)

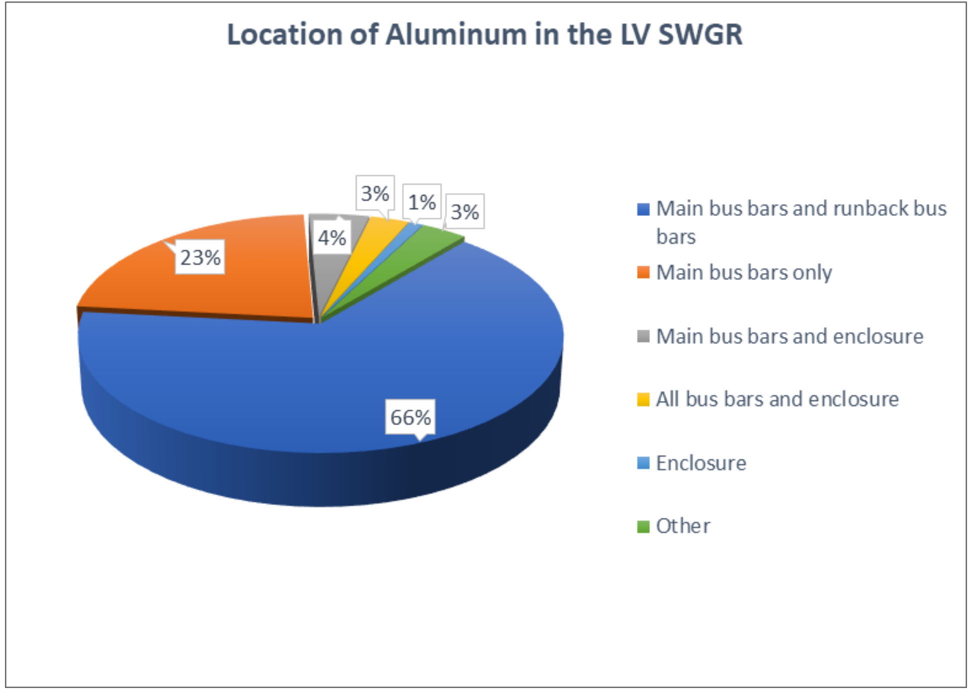


MG SWGR testing with uninsulated bus work is not representative of the majority of plant configurations

EPRI Insights from HEAF-Al Survey Responses

- Medium Voltage Switchgear (MV SWGR)
- Low Voltage Switchgear (LV SWGR) / Load Centers
- Iso-Phase Bus Ducts (ISBDs)

Insights for LV SWGR with Aluminum



- For >96% of LV SWGR aluminum is located in the bus bars (predominantly the main bus bars)
- Operating experience (OE) shows all LV SWGR HEAFs occurred
  - At the breaker stabs, with breaker stabs composed of Copper
  - There are no OE events with LV SWGR HEAFs initiating at the bus bars
- NRC-RES testing of LV SWGR in August 2019, shows it is difficult to sustain an arc in LV SWGR
  - Arc could not be sustained at 480Vac when initiating at main bus bars
  - It was difficulty to sustain an arc at 600Vac when initiating at main bus bars. Only able to sustain and arc 1 out of 5 times, and damage was limited.
  - Even if you could sustain an arc in LV SWGR, EPRI conservative study results show potential impact in PRA is minimal

LV SWGR is very difficult to sustain an arc
Faults initiated at the bus bars are not representative of OE (@ Copper breaker stabs)
Current ZOIs are likely conservative for LV SWGR

EPRI Insights from HEAF-AI Survey Responses

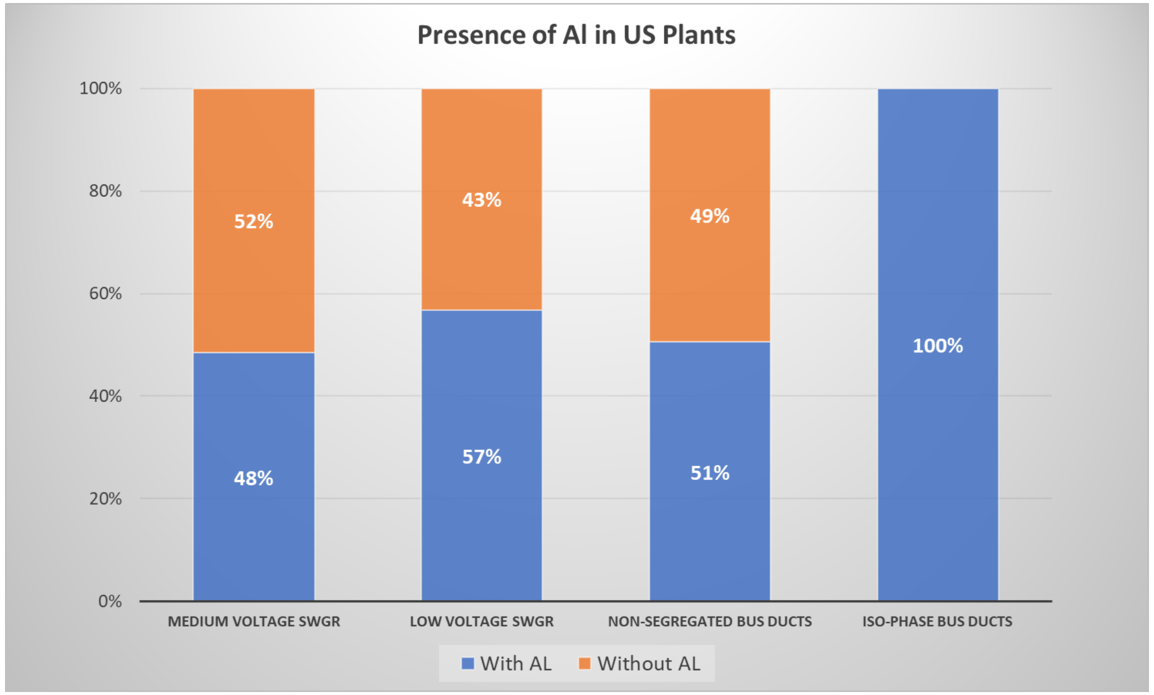
- Medium Voltage Switchgear (MV SWGR)
- Low Voltage Switchgear (LV SWGR) / Load Centers
- Iso-Phase Bus Ducts (ISBDs)

Insights for Iso-Phase Bus Ducts

- 100% of survey respondents have Aluminum in iso-phase bus ducts
- Aluminum is the standard versus Copper for iso phase bus ducts due to
  - Improved electrical properties including less electrical losses and heat
  - Lighter -> less supports, mounting hardware, cost
  - Magnetic properties associated with Copper in this application
- NRC-RES test plan has no intended iso-phase bus duct testing
  - The test facility in the US cannot support such testing
  - Voltage & current requirements (>200kA peak) exceed capability
- Current ZOI for iso-phase bus ducts in NUREG/CR-6850, Supplement 1, FAQ 07-0035 already includes Aluminum
  - Iso-phase bus events analyzed (all contained Al)
  - Establishes 5-foot radial sphere for ZOI

The current ZOI for iso-phase bus ducts already includes any impact of Aluminum

Summary of Testing Insights based on Survey Results



- US Fleet
  - Aluminum exists and has existed across the US fleet in MV SWGR, LV SWGR, iso-phase and non-segregated bus ducts.
  - Majority of plants have Al in multiple types of SSCs
  - Issue not based on any observation in OE suggesting substantially larger ZOIs for HEAFs involving Aluminum
- MV SWGR
  - Horizontal draw-out style representing more than 80% of MV SWGR with Aluminum in the plants
  - Most faults initiate at the breaker stabs which are made of copper
  - >85% of bus work (where Al exists) is insulated
  - For many MV SWGR buses fed from SATs, transformer backup protection would clear a fault very quickly, thus current ZOI is expected to be bounding
- LV SWGR
  - OE and testing both demonstrate that it is very difficult to achieve and maintain an arc in LV SWGR
  - OE suggests that arcs in LV SWGR have all initiated at the breaker stabs which are copper. Plants do not have Aluminum at the LV SWGR breaker stabs
  - Sustaining an arc in LV SWGR long enough to propagate to Al location may be even more challenging. The current ZOI is expected to be bounding.
- Iso-phase bus ducts
  - 100% of iso-phase bus ducts are Al
  - Current ZOI for iso-phase bus ducts (5ft radial sphere) in NUREG/CR-6850, Supplement 1, FAQ 07-0035 already includes Aluminum

EPRI Analysis based on HEAF Survey Results
Insights related to Potential Changes in Risk

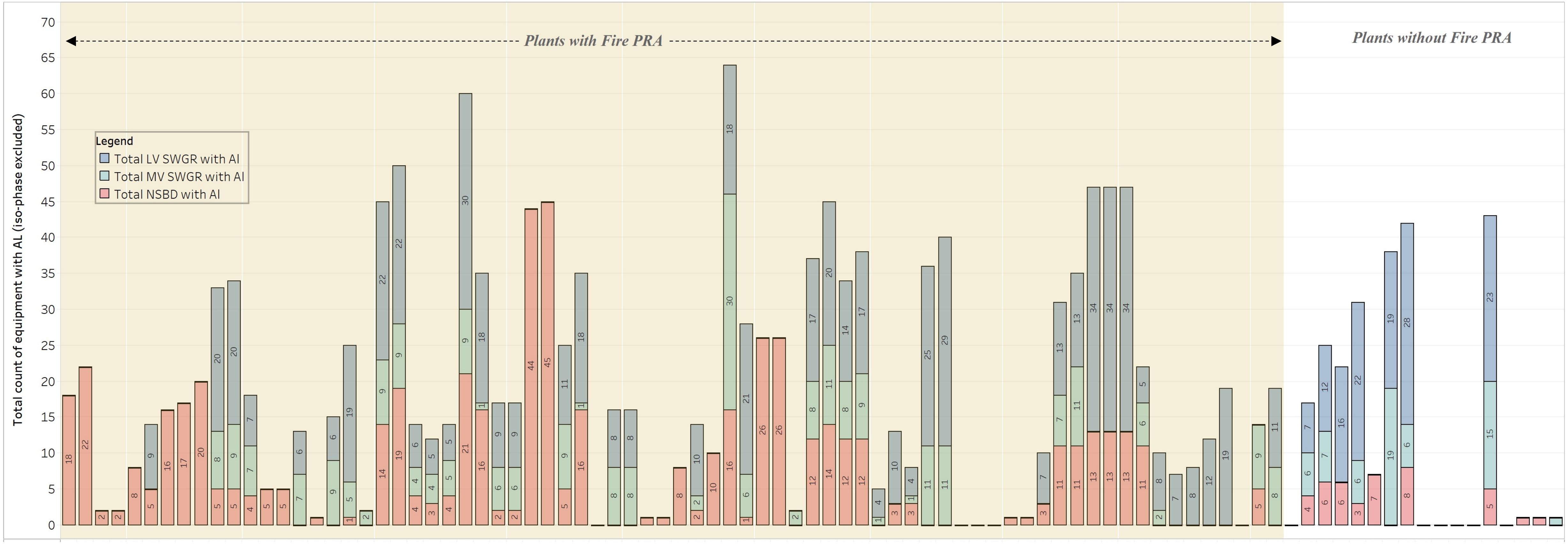
Summary of the EPRI Detailed Analysis of Survey Data

- Since Aluminum is present in all plants, analysis and interpretation of the data is necessary to achieve insights
  - 100% of plants have Aluminum in their isophase bus ducts, and
  - 87% of plants have at least some Aluminum in non-seg bus ducts, MV SWGR, or LV SWGR
  - EPRI completed a detailed analysis to understand the generic implications of the results.
  - Since proposed HEAF ZOI’s for various alignments are still in development, EPRI used an intentionally bounding and conservative stepwise approach using newly developed concepts of the DRAFT HEAF methodology
- Stepwise structured approach uses:
  - Current Fire PRA data
  - Location of the Aluminum in the plants in which specific SSCs
  - Worst case “full-room burn” scenario as conservative surrogate for hypothetically larger ZOI due to Aluminum
  - Plant electrical distribution system design and protection detail - included electrical distribution systems of every plant to understand where components with Al were powered from and what protection was available
  - More detailed PRA HEAF modeling concepts being developed by the joint EPRI – NRC-RES working group

EPRI detailed analysis uses realism where data is known and intentionally conservative approaches where values are not yet known

Plants Considered in the EPRI Detailed Analysis

- EPRI detailed analysis used Fire PRA CDF as a metric for determining whether the plant can be categorized "*unlikely to be impacted*" by any hypothetically larger ZOIs for HEAF involving Al
- There are 19 plants that do not have Fire PRAs.
  These plants do have Aluminum in components of interest but were excluded from the EPRI detailed analysis due to lack of PRA data. 7 of these plants have Al only in ISBDs and therefore no change in risk is expected.



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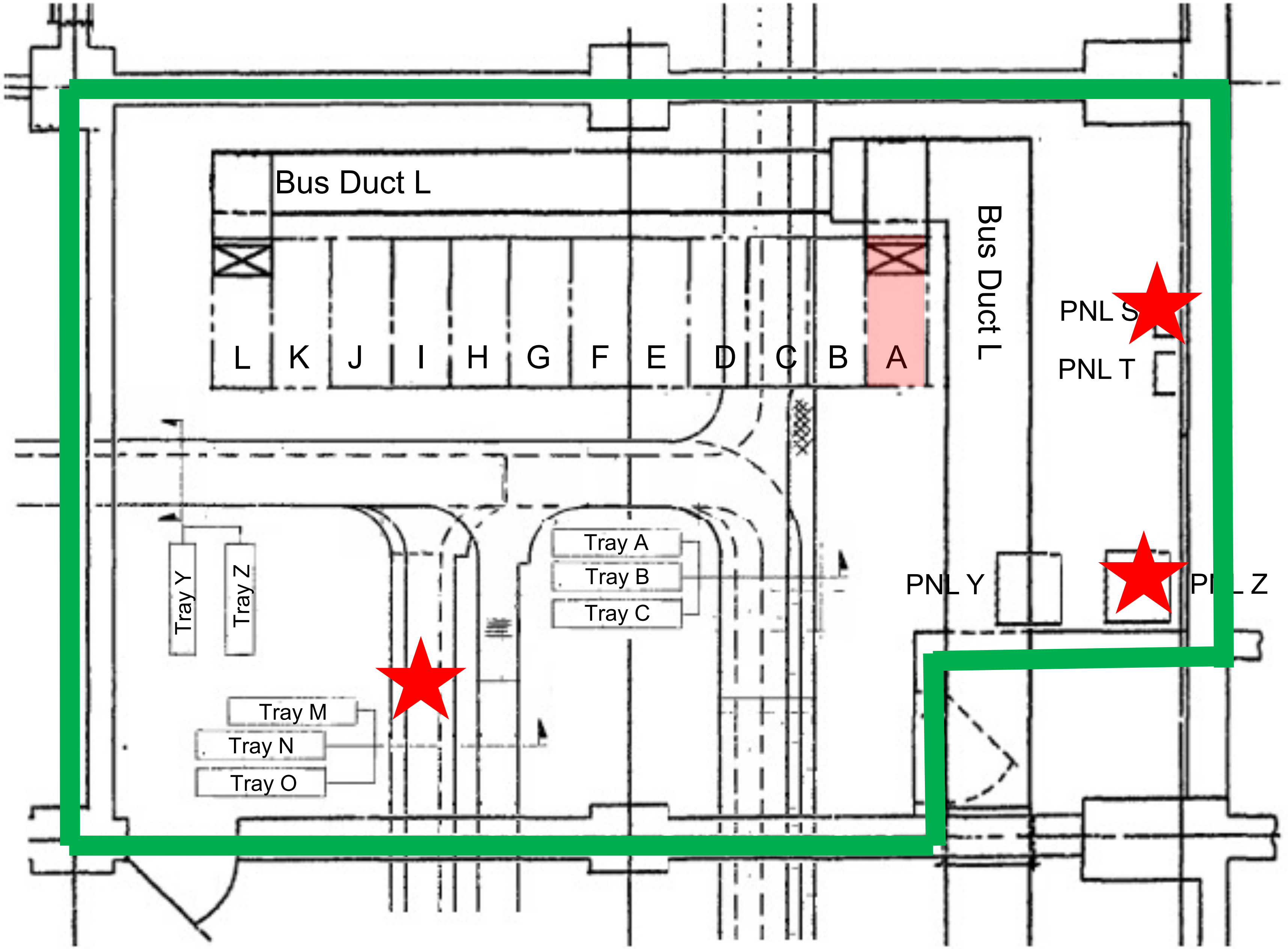
Two critical concepts to understand

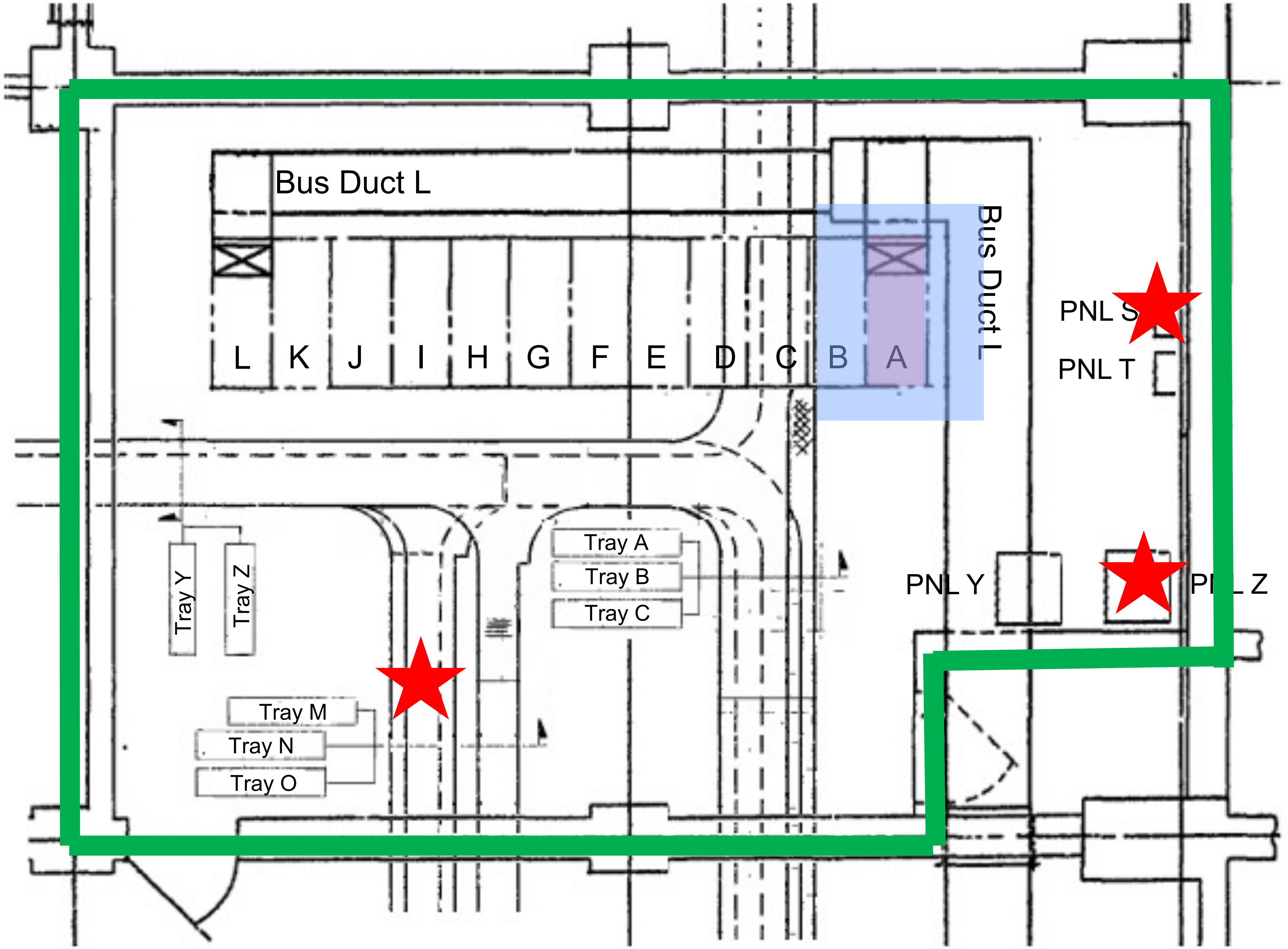
- “Full Room Burn” (FRB)
- “Fault Clearing Time” (FCT)

Conservative Nature of Assuming a "Full Room Burn" (FRB)



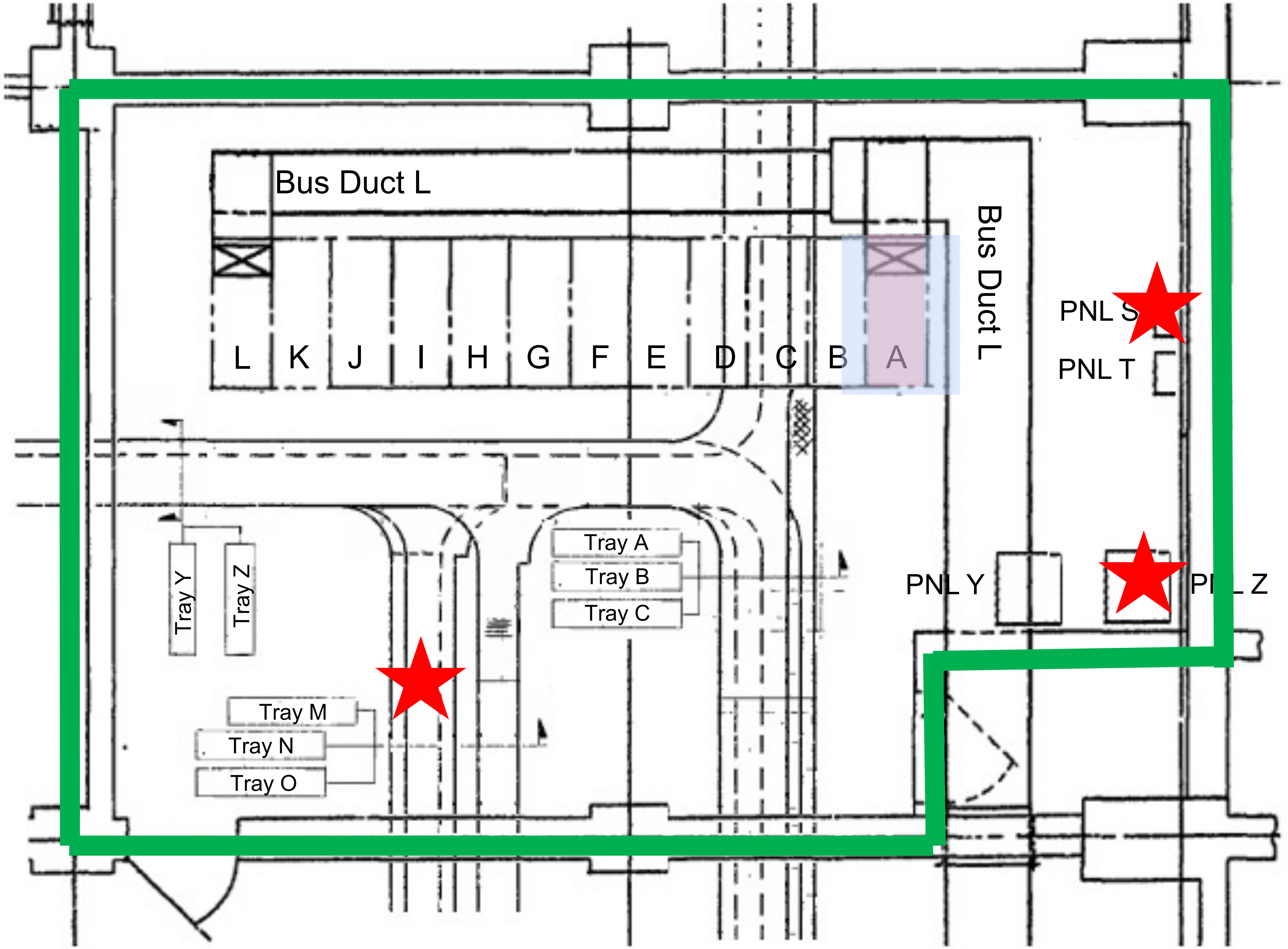
- A given "fire area" in the Fire PRA (outlined)
- SSC "A" is susceptible to HEAFs and contains Aluminum
- Some "targets" are important in the fire PRA (starred)

Conservative Nature of Assuming a "Full Room Burn" (FRB)



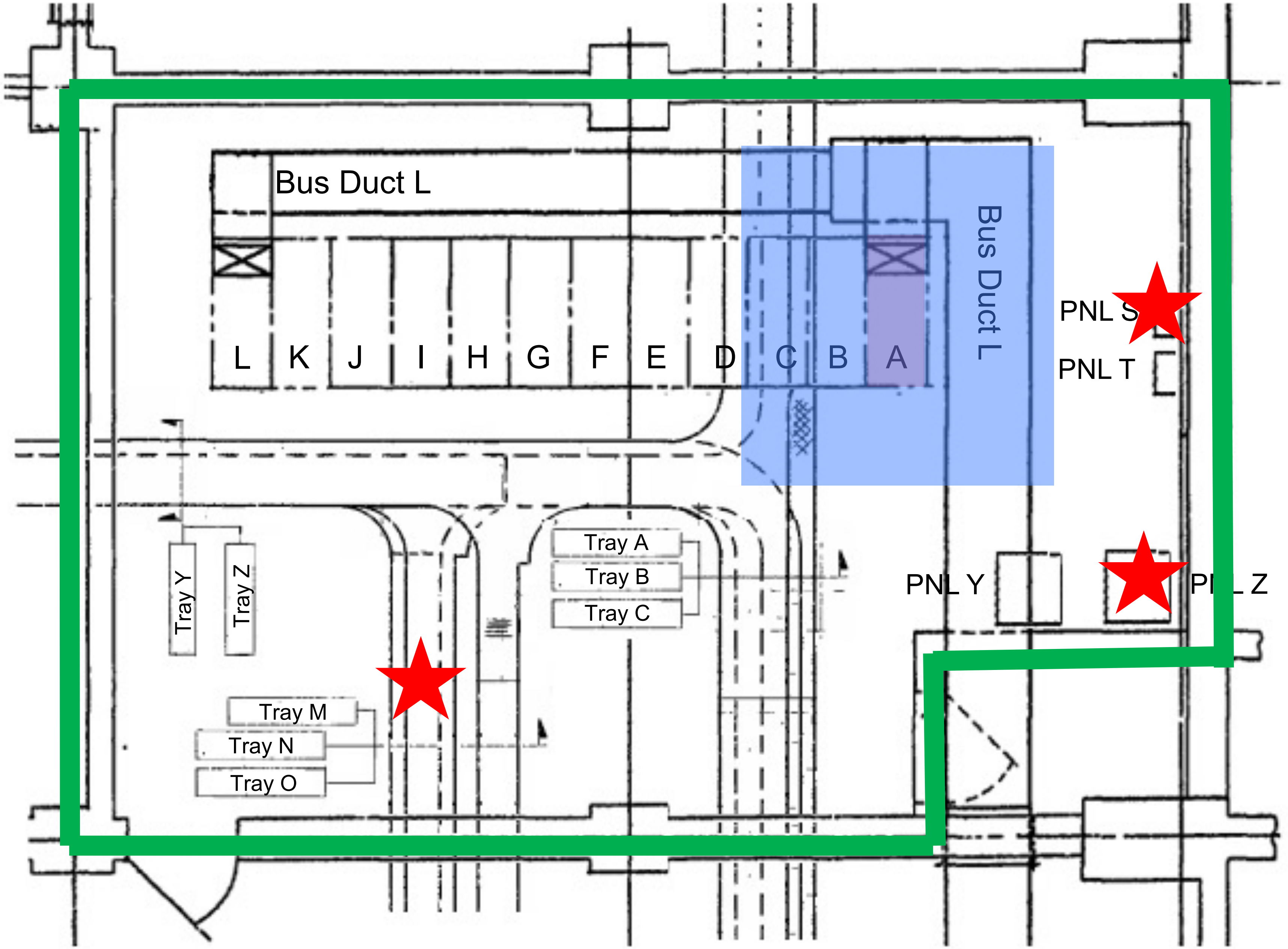
- Current ZOI

Conservative Nature of Assuming a "Full Room Burn" (FRB)



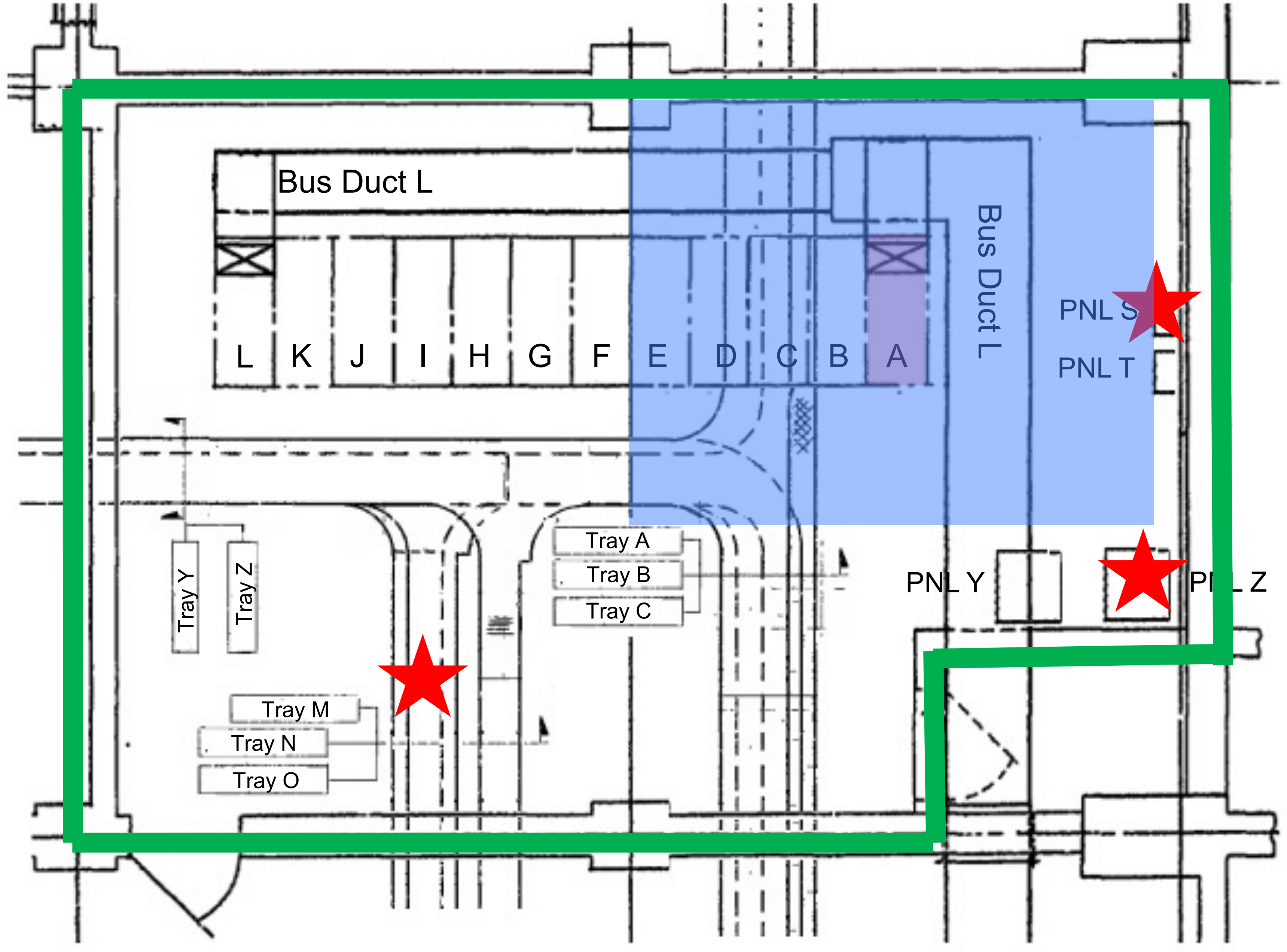
- Current ZOI
- "Updated ZOI"
  - Decrease?

Conservative Nature of Assuming a “Full Room Burn” (FRB)



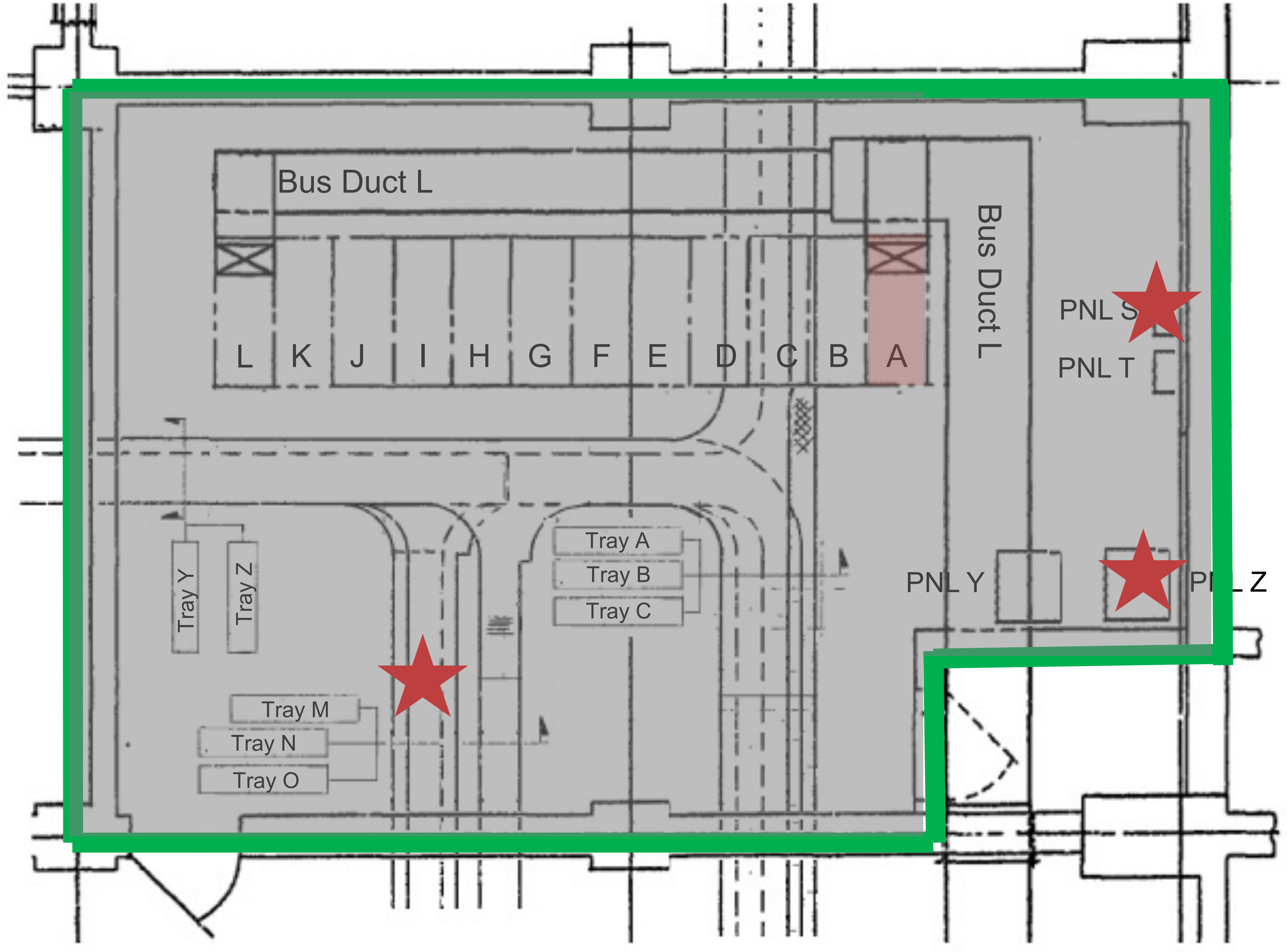
- Current ZOI
- “Updated ZOI”
  - Decrease?
  - Increase 1?

Conservative Nature of Assuming a "Full Room Burn" (FRB)



- Current ZOI
- "Updated ZOI"
  - Decrease?
  - Increase 1?
  - Increase 2?

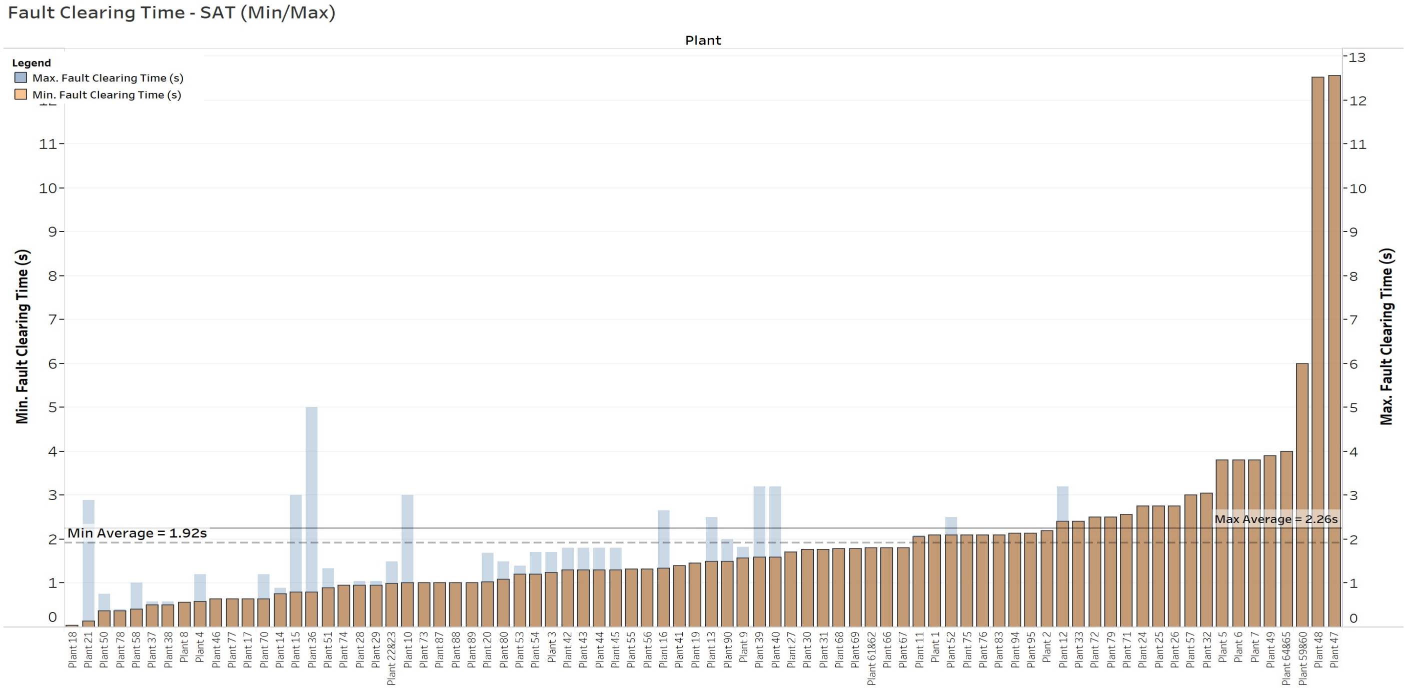
Conservative Nature of Assuming a "Full Room Burn" (FRB)

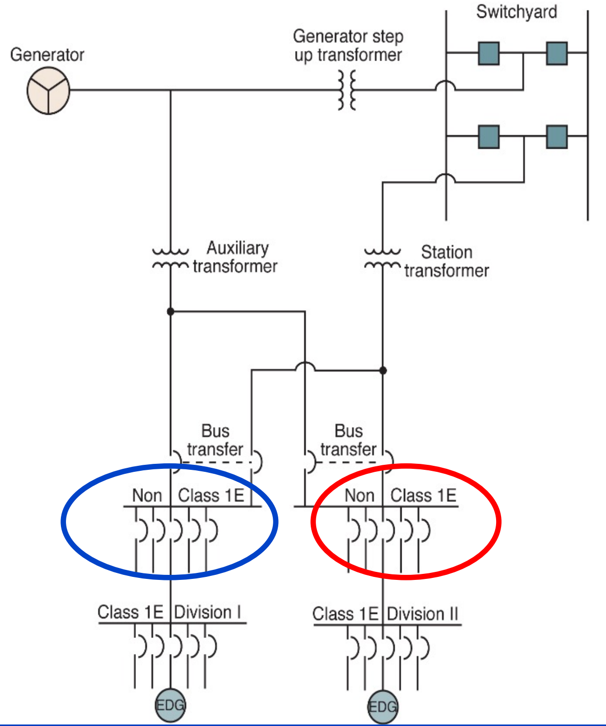


- Current ZOI
- "Updated ZOI"
  - Decrease?
  - Increase 1?
  - Increase 2?
- FRB
  - Bounds any impacts of larger ZOIs
  - Often simplified if not significant in the PRA
  - e.g., assumes CCDP = 1

Importance of Fault Clearing Time (FCT) for Limiting Duration of HEAFs

- MV SWGR powered by the Unit Auxiliary Transformer (UAT) are susceptible to long duration faults if generator output breaker fails and no backup protection is available
- For the MV SWGR powered by the Station Auxiliary Transformer (SAT), the fault duration is dictated by the transformer backup protection
  - The timed overcurrent setpoint and associated fault clearing time, defines the duration of a HEAF
  - The average fault clearing time for the MV SWGR when powered by the SAT is <2 sec for the US fleet





For large majority of US plants any HEAF in MV SWGR powered by SAT would be less than 2 sec

Fault Clearing Time (FCT) for Backup Protection

- HEAFs involving Aluminum have been identified as a potential concern in “long duration” events
  - OECD (NEA/CSNI/R(2017)7) testing cited in NRC IN 2017-004 as the basis for the pre-GI on HEAF involving Al was for two tests with durations of 7 sec and 4.3 sec
  - NRC Draft Test Plan (Phase 2), Table 1 identified HEAF durations of interest were all greater than 2 sec (Robinson, Diablo Canyon, Prairie Island, San Onofre, and Ft. Calhoun)
  - No OE or experimental results indicating energy differences between HEAF involving Aluminum and Copper at 2 sec or less
- The finding that a large majority of plants have fault clearing times of <2 sec when powered from the SAT means that MV SWGR in these locations have backup protection to prevent long-duration HEAFs.

The current ZOI for MV SWGR bounds HEAF events with Aluminum of 2 seconds or less

Summary of the EPRI Detailed Analysis Approach

Step	Bases
Step 1 – Is there Aluminum present?	If there is no Aluminum present, then there is no impact of a larger ZOI due to Aluminum
Step 2 – If Aluminum is present, does the CDF go up assuming a full-room burn in the locations with Aluminum?	Assuming full-room burn is a conservative screening tool. Since we do not know all the SSCs nearby, and the ZOIs specifically for Al versus non-Al, a full room burn was hypothesized. If the CDF does not go up, even assuming a full room burn, it means that an expanded ZOI due to the Aluminum has no impact.
Step 3 – Is fast acting backup protection available for the MV equipment containing Aluminum?	When the backup protection of the SAT has a fault clearing time of <2 sec, a long-duration HEAF is not expected even with failure of the primary protection circuit breaker. Since the potential larger energy release due to Aluminum only happened in testing situations where the HEAF sustained for >4 sec, there is no expected difference between Copper and Aluminum for HEAFs where the fault clearing times <2 sec. Therefore, no increase in ZOI for the MV SWGR normally fed by the SAT for fault durations of <2s is expected. Also in this step, current LV SWGR and IPBD ZOIs are maintained.
Step 4 – What other information is known about the properties of electrical distribution systems and susceptibility to HEAFs?	This step uses the draft methodology developed by the joint working group and provides greater fidelity than the "one-size-fits-all" HEAF modeling approach. The method includes the FCT from Step 3, along with credit for the protection scheme design and frequency apportioning based on intermediate bus switchgear breaker protection, arc fault location, and the availability of a generator circuit breaker.

Using the current NUREG-6850 "one size fits all" approach over-emphasizes the potential significance of HEAF involving Aluminum

EPRI Approach for Detailed Analysis of HEAF Survey Data

Step 0 — Plants with Fire PRA

Step 1 — Plants with Aluminum

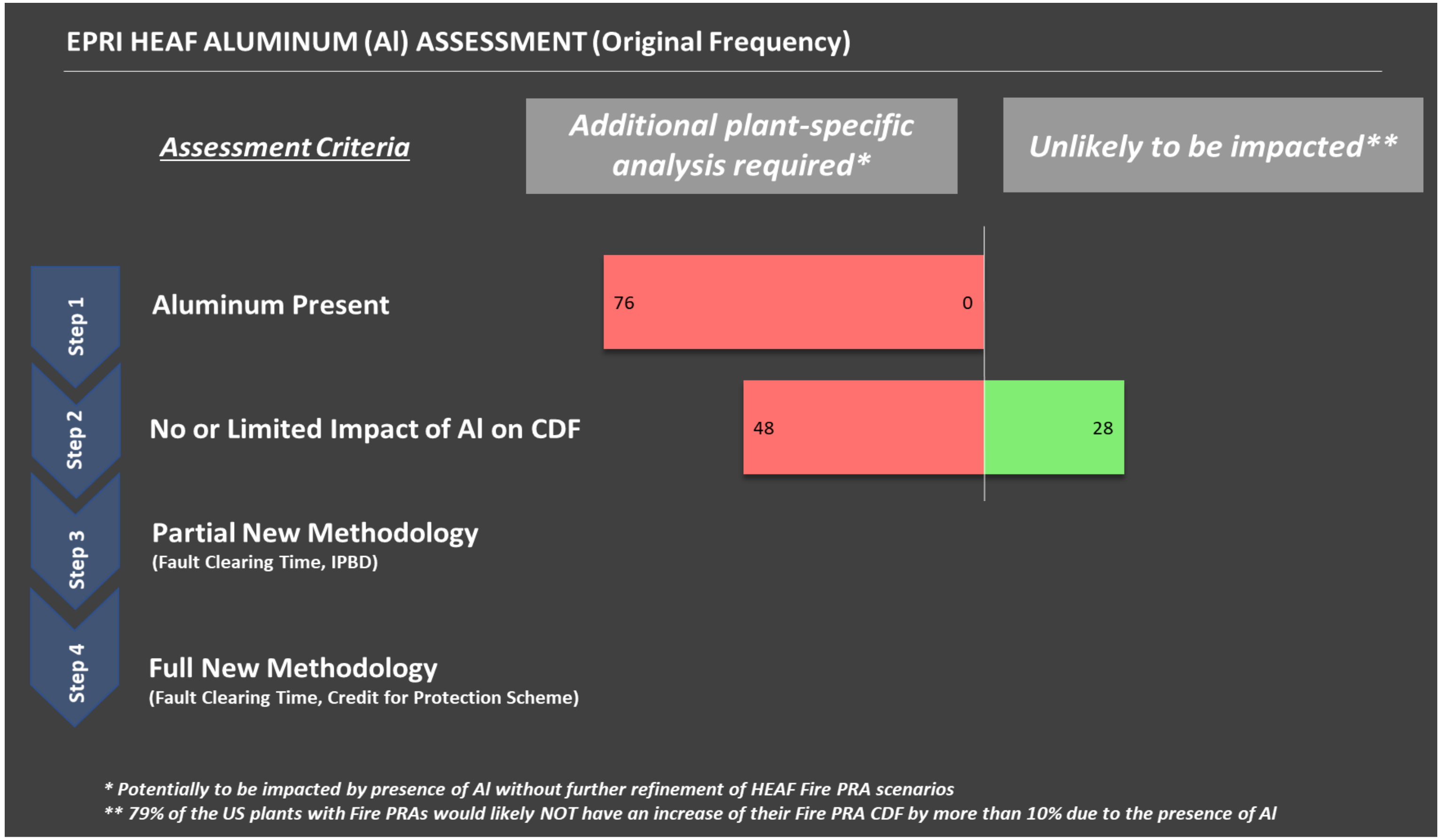
Step 2 — Comparison between Case Study 1 (Base) and Case Study 2 (FRB)

Step 3 — Comparison between Case Study 1 (Base) and Case Study 3 (FCT)

Step 4 — Comparison between Case Study 1 (Base) and Case Study 4 (Draft Method)

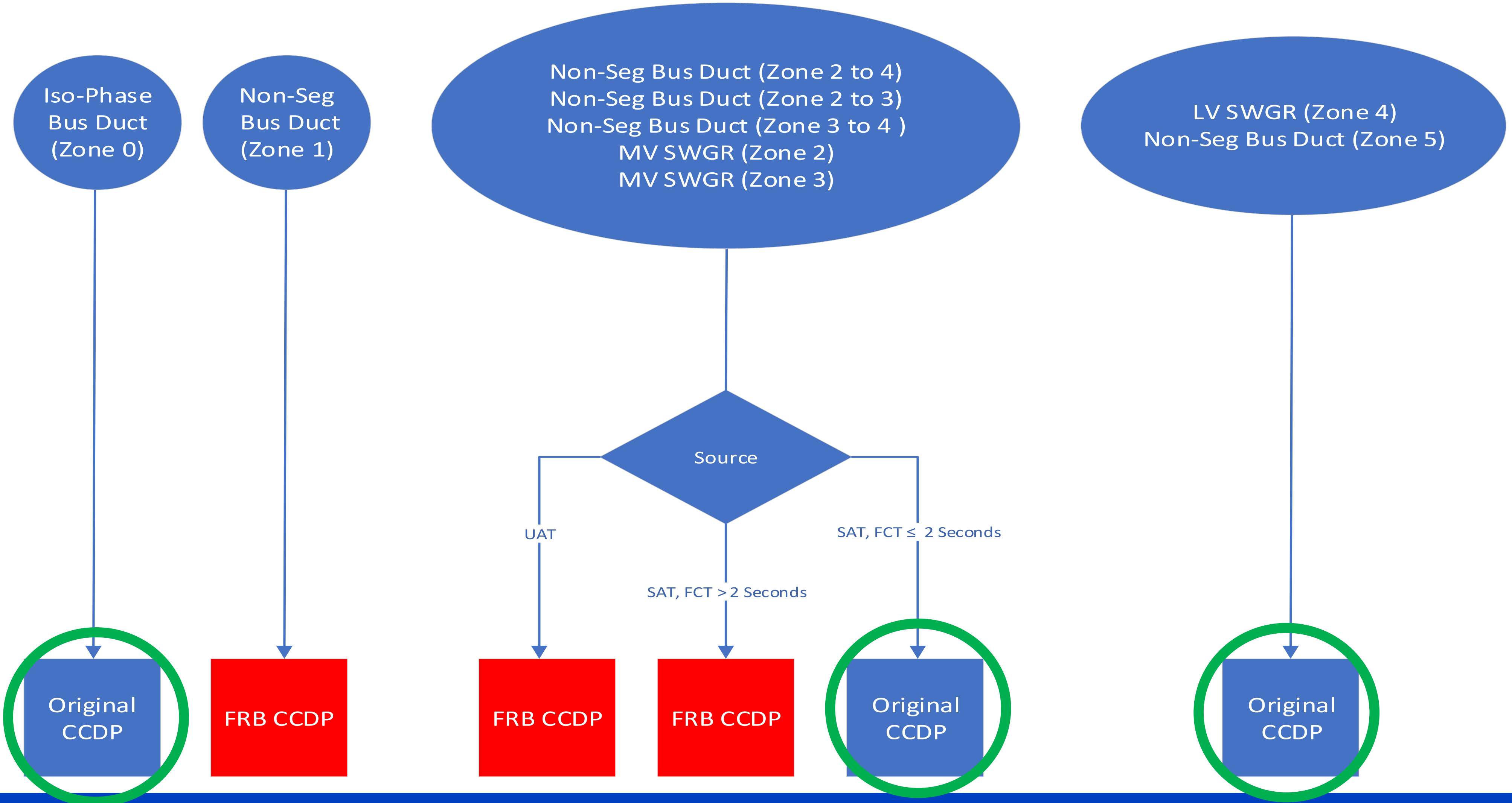
- Steps in the EPRI detailed analysis were performed iteratively using sensitivity case studies based on
  - Current Fire PRA data
  - Location of the Aluminum in the plants
  - Worst case “full-room burn” scenario as conservative surrogate for potentially larger ZOI due to Aluminum
  - Plant electrical distribution system design and protection detail including fault clearing times (FCT)
  - More detailed PRA HEAF modeling concepts being developed by the joint EPRI – NRC-RES working group
- Information used in Steps 0-4 above:
  - Uses the data from the HEAF-Aluminum survey to estimate the change in the total Fire CDF
  - Where data is unknown (i.e., proposed realistic ZOIs for HEAF with Aluminum) an intentionally conservative and bounding surrogate was used to address the potentially larger ZOI (i.e., a full room burn (FRB) was hypothesized to represent a bounding worst-case scenario)
- A 10% increase in the total Fire CDF was used as a threshold for deciding if a unit would be *“potentially impacted”* or *“unlikely to be impacted”* due to aluminum
  - The 10% threshold corresponds to an average Fire PRA ΔCDF of 5E-06, remaining below the 1E-05 threshold
  - The criteria of 10% increase was applied solely to the Fire PRA ΔCDF, other contributors are not considered

Step 1 – Does the plant have Aluminum?
Step 2 – Does the CCDP increase assuming a FRB?



- *"Additional plant-specific analysis required"* means that risk impacts are not evaluated in the EPRI analysis
  - With the conservative approach shown, it is not possible to say there will not be a risk increase
  - However, no specific risk values or changes in risk can be calculated without the necessary ZOI values
- *"Unlikely to be impacted"* means the plant is unlikely to show significant risk increase even with bounding ZOI for Aluminum - based on:
  - Known data and plant design information
  - Currently Draft PRA modeling approaches for HEAF being developed by working group
  - Bounding/conservative approaches to address the unknown ZOI involving Aluminum (i.e., FRB assumption)

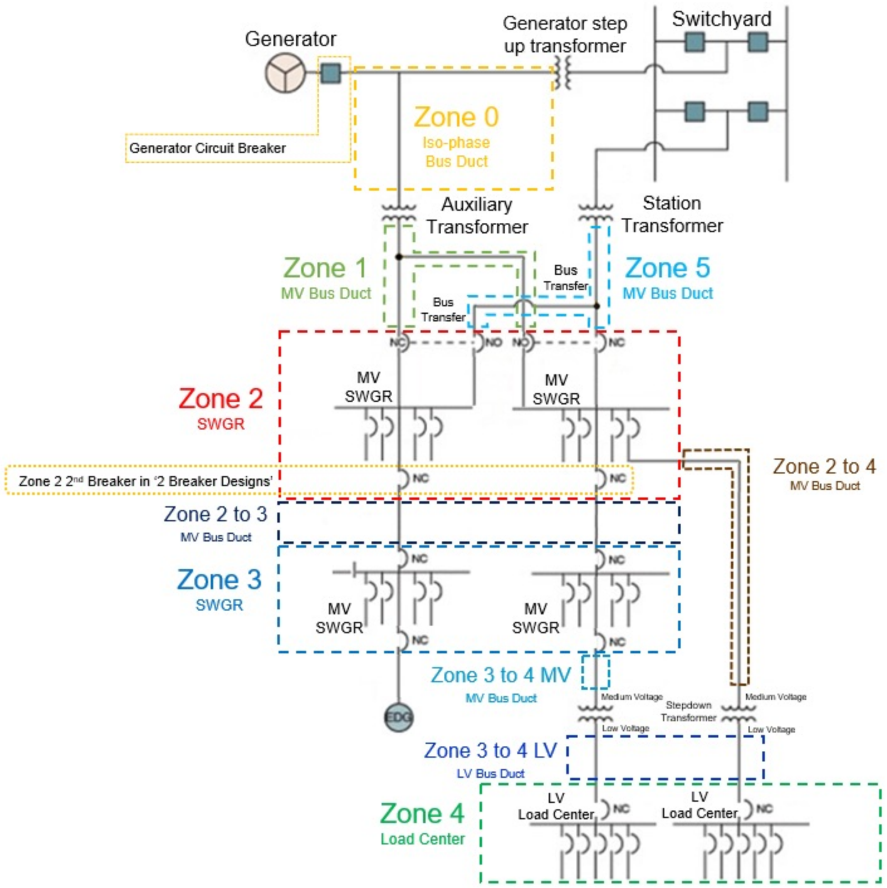
Step 3: ISBD, LV SWGR, and FCT Insights added to Analysis



This case study introduces realism by recognizing available backup protection while still applying a conservative FRB for the unknown Aluminum ZOI

Step 4: Draft HEAF Refined Modeling Guidance

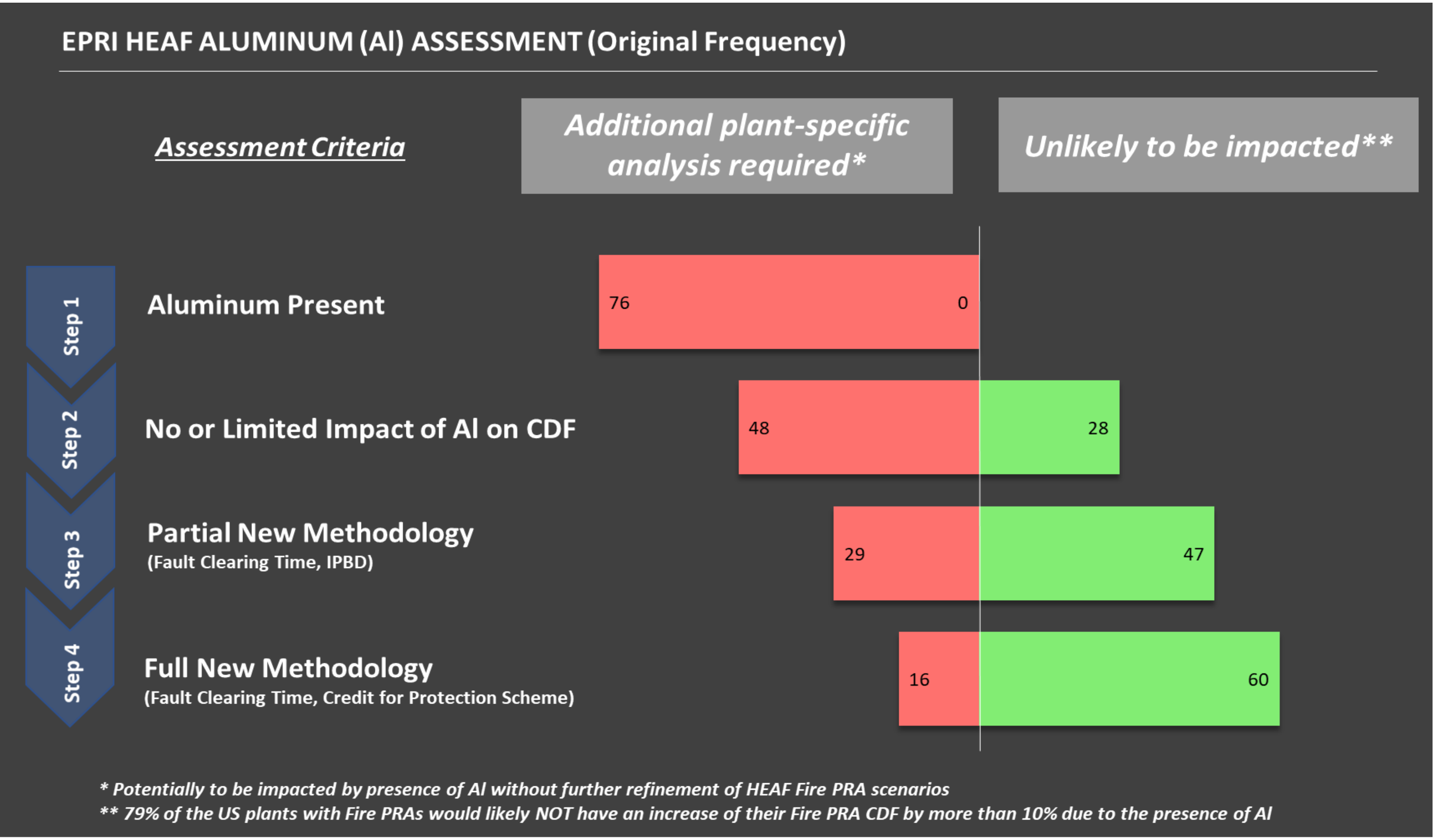
- Applies the more detailed draft PRA HEAF modeling guidance in development by the joint EPRI – NRC-RES working group
  - Consequence concepts described in Step 3
  - Credit for the protection scheme design
  - Frequency apportioning based on:
    - Intermediate bus switchgear breaker protection
    - Arc fault location (Supply vs. Load)
    - Generator circuit breaker (when available)



Example figure indicating that different SSCs have different levels of protection available in different zones

Final HEAF Refined Modeling Guidance to be a consensus product based on HEAF WG

Step 3 – IPBD, LV SWGR, and FCT Considerations
Step 4 –DRAFT Fire PRA HEAF modeling



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  - Bounding/conservative approaches to address the unknown ZOI involving Aluminum (i.e., FRB assumptions)

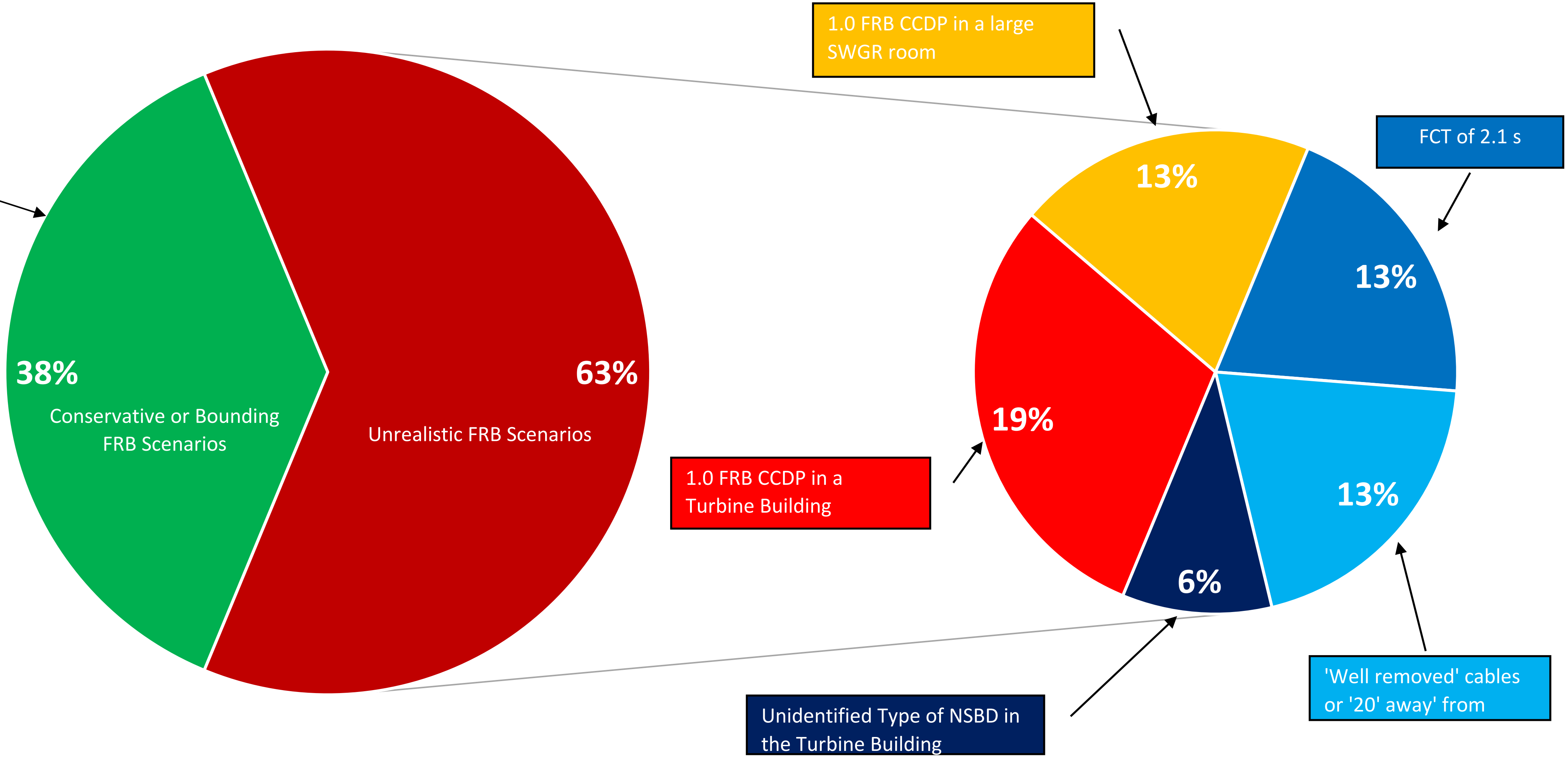
What do we know about the 16 “unscreened” plans?

- The EPRI analysis that did not screen out these plants is intentionally and demonstrably conservative
- For many of these plants, the FRB scenarios provided in the survey and used for this assessment are too conservative and unrealistic:
  - Plant X
    - NSBD containing Al
    - Located in “the yard”
    - Calculated HEAF CCDP was 0 while the FRB CCDP was 1. This is indicative simplified analysis when creating the PRA model, for an area that was known to not be a risk contributor.
  - Plant Y
    - MV SWGR containing Al
    - Located in the turbine building
    - Calculated HEAF CCDP goes from 1E-03 to 1 for the FRB CCDP. In this case, the FRB assumes loss of the entire turbine building which is not practical in reality

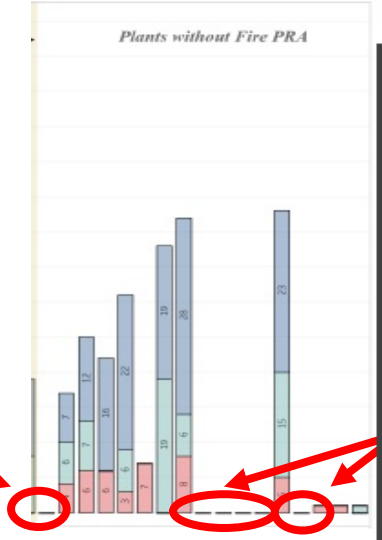
EPRI analysis does not say these plants have a risk increase
FRB is conservative and, any many cases, known to be unrealistic

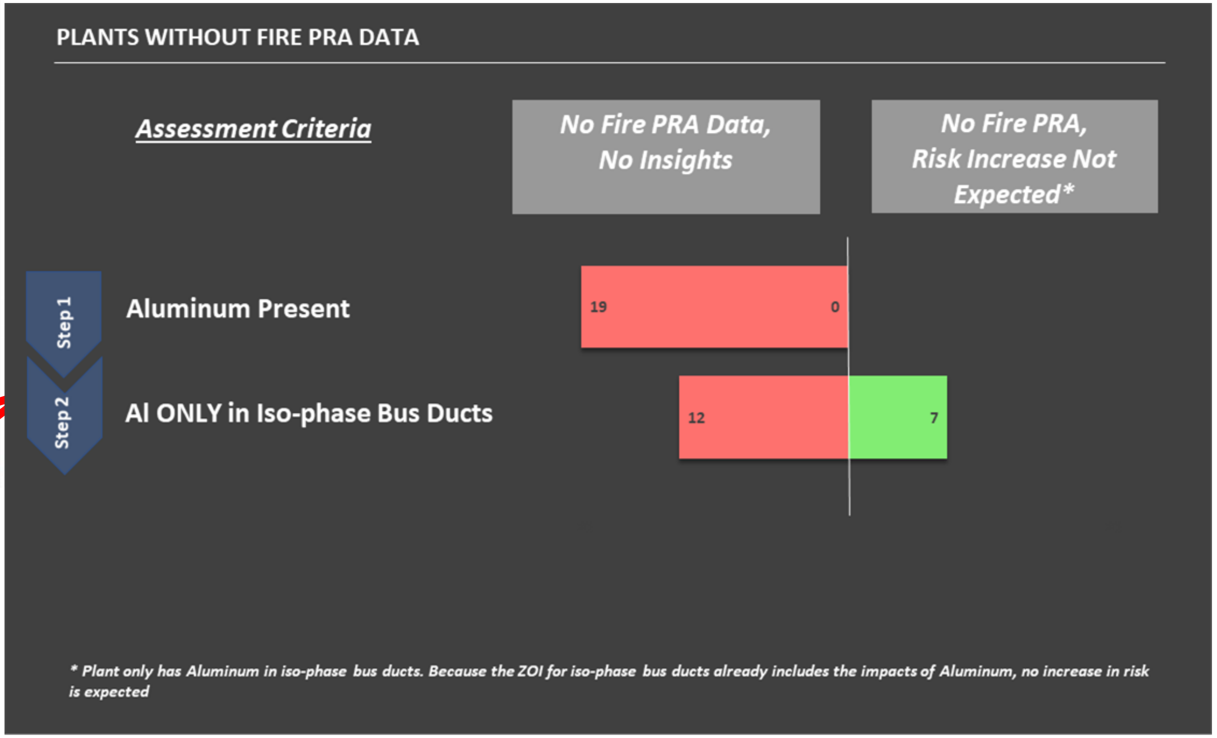
Most “Unscreened Plants” have Scenarios known to be “Unrealistic” *in terms of the FRB Assumption Used*

FRB assumes complete loss of everything in the fire area which would mean ZOI’s increase 10’s of feet. WG is currently arguing about inches, not 10’s of feet.



Summary of the EPRI Detailed Analysis Results
Plants that Did Not Provide Fire PRA Data





- *"No Fire PRA data, No risk insights"* for this unit means that risk impacts are not yet known
  - The unit has Aluminum in at least one MV SWGR, LV SWGR, or non-segregated bus duct in addition to the iso-phase bus ducts.
  - Because no Fire PRA data was available, EPRI could not analyze potential impacts for this plant.
  - It is assumed that these plants satisfy Appendix R criteria
- *"No Fire PRA data, Risk Increase Not Expected"* for this unit means the plant is unlikely to show significant risk increase based on:
  - This unit did not provide Fire PRA data; however, the unit indicated that the only location with Aluminum is the iso-phase base ducts.
  - Because the ZOI for iso-phase bus ducts (NUREG/CR-6850, Supplement 1, FAQ 07-0035) already includes the impact of Aluminum, no increase in risk due to the presence of Al is expected.

Breakdown of EPRI Detailed Analysis Results for 95 plants in US

Categorization	Number of Units	Of units that provided PRA Data (76 units)	Total % of units surveyed (95 units)
Additional plant-specific detail required to validate a specific delta risk	16	21%	17%
Unlikely to be impacted	60	79%	63%
No Fire PRA, and no insights available	12		13%
No Fire PRA, but not likely to have increased risk	7		7%

HEAF Key Conclusions

- Aluminum exists in all plants and many components
- Detailed survey results on the location and types of SSCs containing Aluminum provide valuable information for the purpose of informing NRC-RES proposed testing on HEAFs
- The presence of Al is NOT directly related to increased risk
- Actual changes in plant risk from Al involved in HEAFs cannot be determined until realistic ZOIs are determined and applied with the newly developed Fire PRA modeling guidance for HEAFs
- EPRI bounding assessment using the current Fire PRA data and draft methodology provide high confidence that for large portion of the US plants the AL presence would likely have limited impact

Together…Shaping the Future of Electricity