

A Case Study for Substation Lightning Protection and Risk Evaluation



November 8, 2016

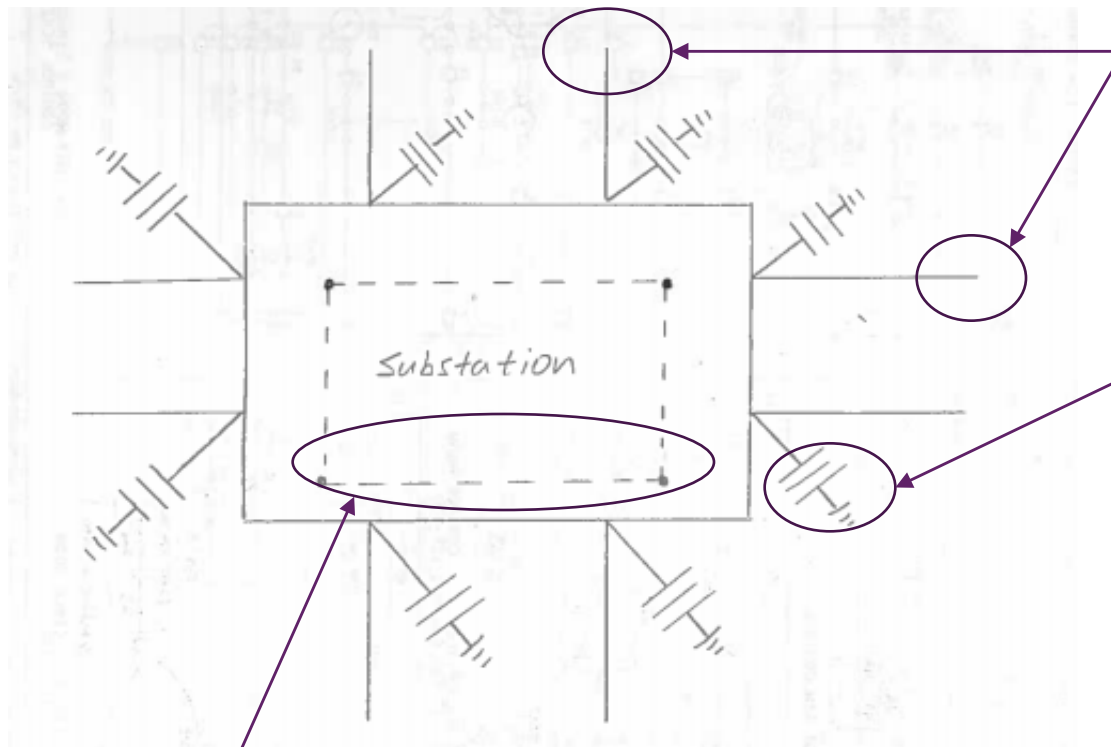
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Content of the Presentation

- Introduction on substation lightning protection, the rolling sphere method and the fixed angle method
- Case Study – lightning shield design for a Substation
 - Keraunic level and ground flash density
 - Risk tolerance of lightning strokes in a substation
- Failure rate between the rolling sphere method and the fixed angle method
- Consequences of outages in an event of a lightning stroke
- Conclusion

Overview – Lightning Protection



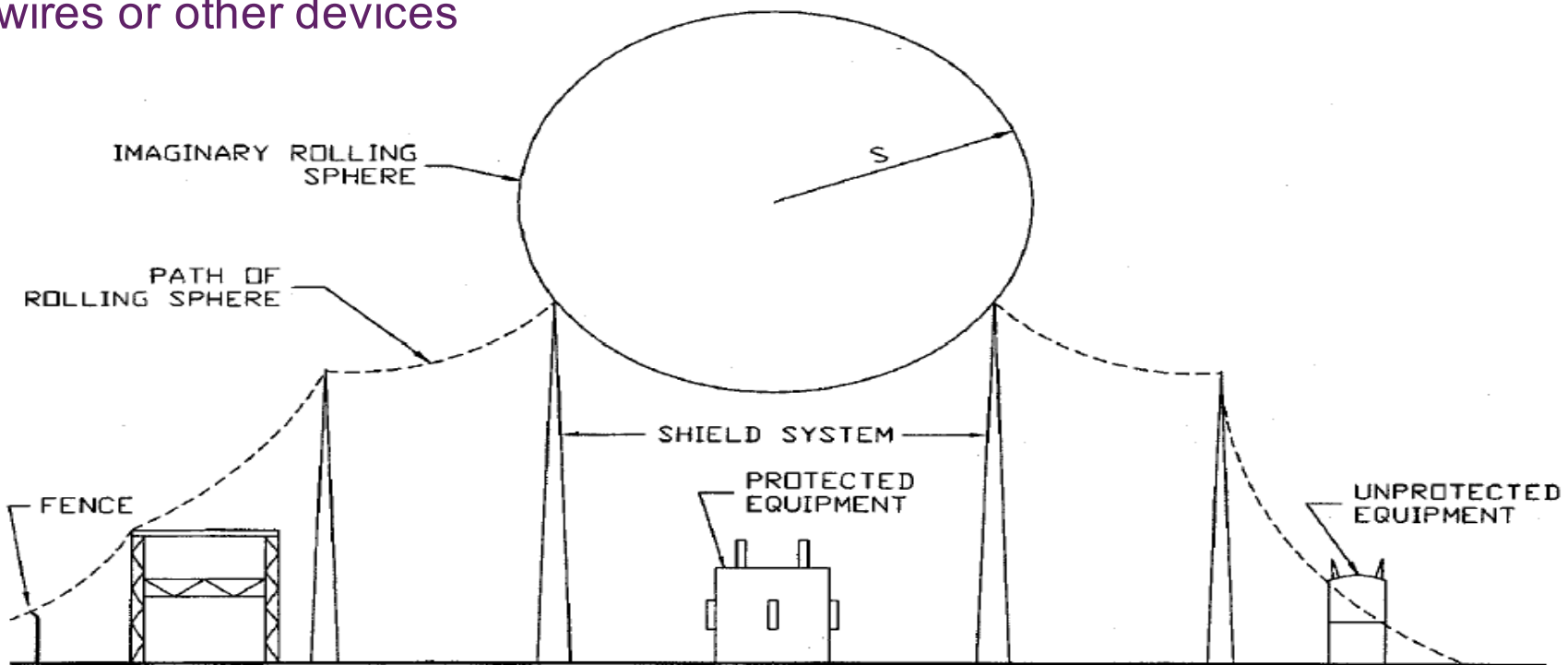
Overhead shield wire through the line

Surge arrester to protect transient and switching over voltage

Lightning masts and shield wires to prevent direct lightning stroke to the substation

Rolling Sphere Method

- An imaginary sphere of prescribed radius over the surface of a substation
- The sphere will roll up and over all grounded metal objects intended for lightning shielding
- A piece of equipment is protected from a direct stroke if it remains below the curved surface of the sphere by virtue of the sphere being elevated by shield wires or other devices



Rolling Sphere Method

Stroke current (I_s) is then defined as:

The equation for stroke current is:

$$I_s = \frac{1.1(BIL)}{\frac{Z_s}{2}} = \frac{2.2(BIL)}{Z_s}$$

or

$$I_s = \frac{0.94(CFO)1.1}{\frac{Z_s}{2}} = \frac{2.068(CFO)}{Z_s}$$

- Surge impedance (Z_s)
- Basic insulation level (BIL)
- Allowable stroke current (I_s)
- Negative polarity critical flashover voltage (CFO)

Rolling Sphere Method

The equation for surge impedance is:

$$Z_s = 60 \sqrt{\ln\left(\frac{2h}{R_c}\right) \ln\left(\frac{2h}{r}\right)}$$

R_c = corona radius

r = radius of the conductor

h = average height of conductor

Strike distance S (radius of the sphere)

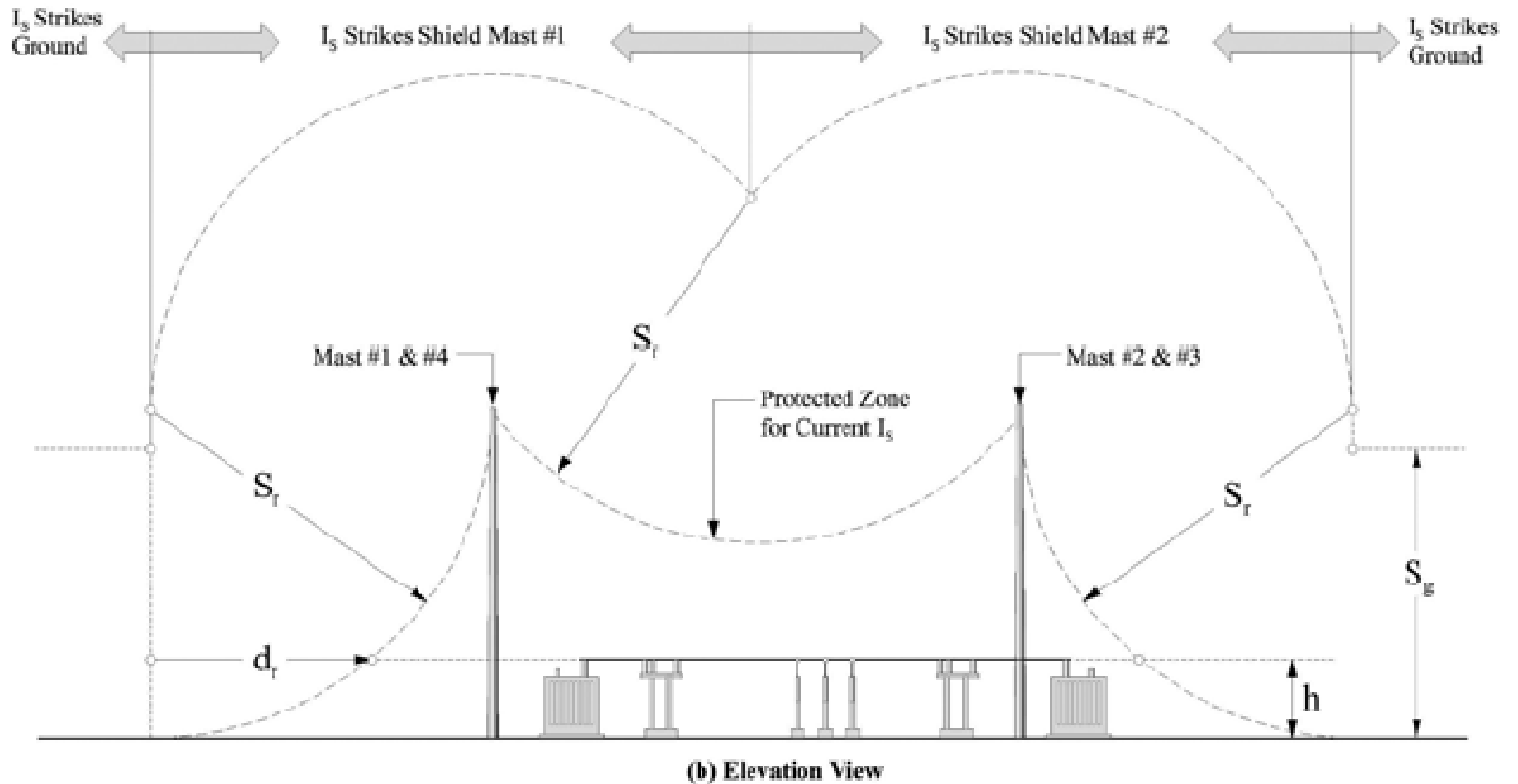
$S_m = 8kI^{0.65}$ as in meter

$S_f = 26.25kI^{0.65}$ as in feet

$k = 1$ for shield wires

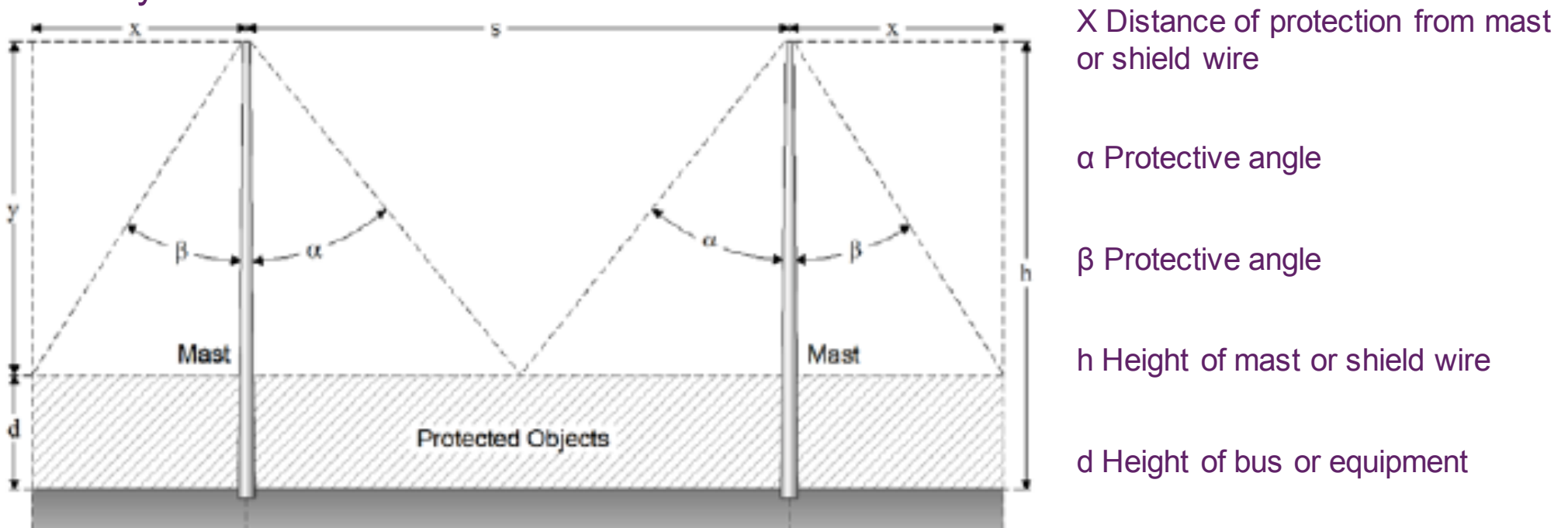
$k = 1.2$ for lightning masts

Rolling Sphere Method



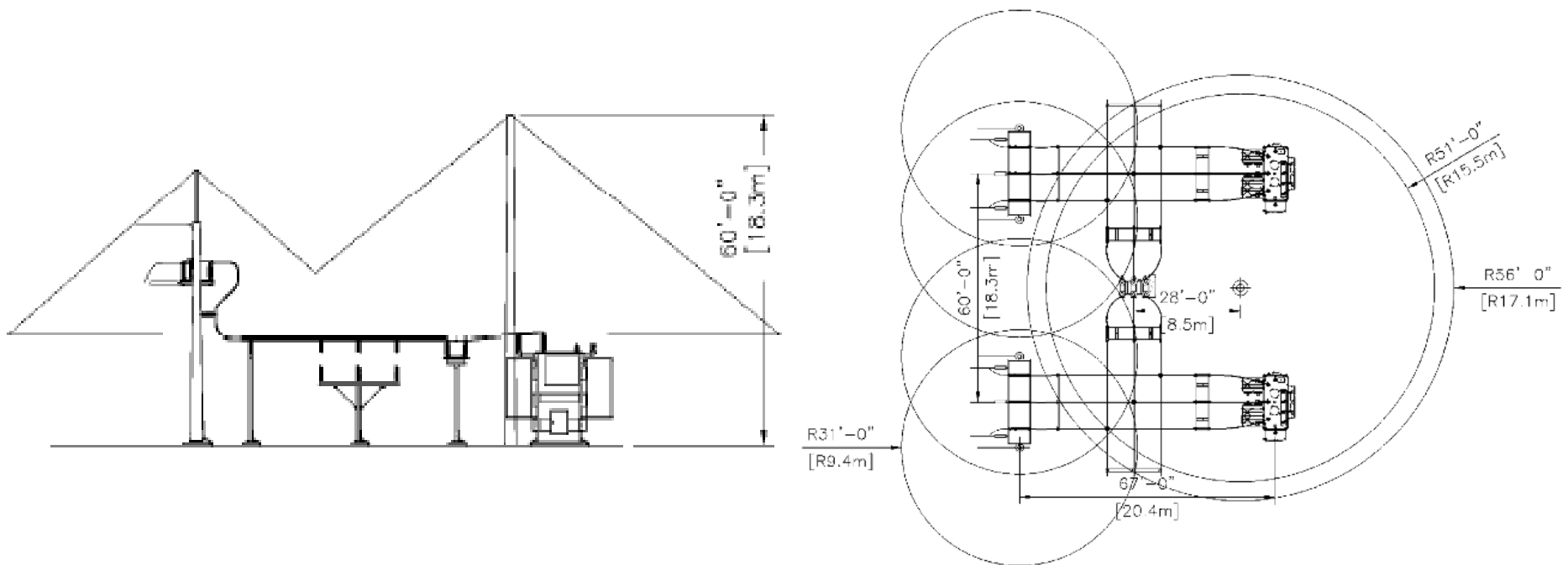
Fixed Angle Method

- Uses vertical angles to determine the number, position, and height of shielding wires or masts.
- The angles used are determined by the degree of lightning exposure, the importance of the substation being protected, and the physical area occupied by the substation.



The area of protection at the height of the equipment is: $X=(h-d) \times \tan\theta$

Fixed Angle Method



- Finding the area of protection X allows us to draw the protection circles for the mast.
- Protective angle changes as the height of the structure increases.

Comparison between the Two Methods

Rolling sphere method

- Requires surge impedance, BIL, to determine stroke current
- Allows strokes that will not cause flashover or damage to enter shielded area
- Failure rate is small (0.05%)

Fixed angle method

- “Rule of thumb” method
- Uses vertical angles to determine:
 - Total number of protection devices
 - Position
 - Height
- With a protective angle of α and $\beta = 45^\circ$ and height of mast up to 15 m (49 ft) the failure rate is approximately 0.2%.

Case Study – Lightning Shield Design

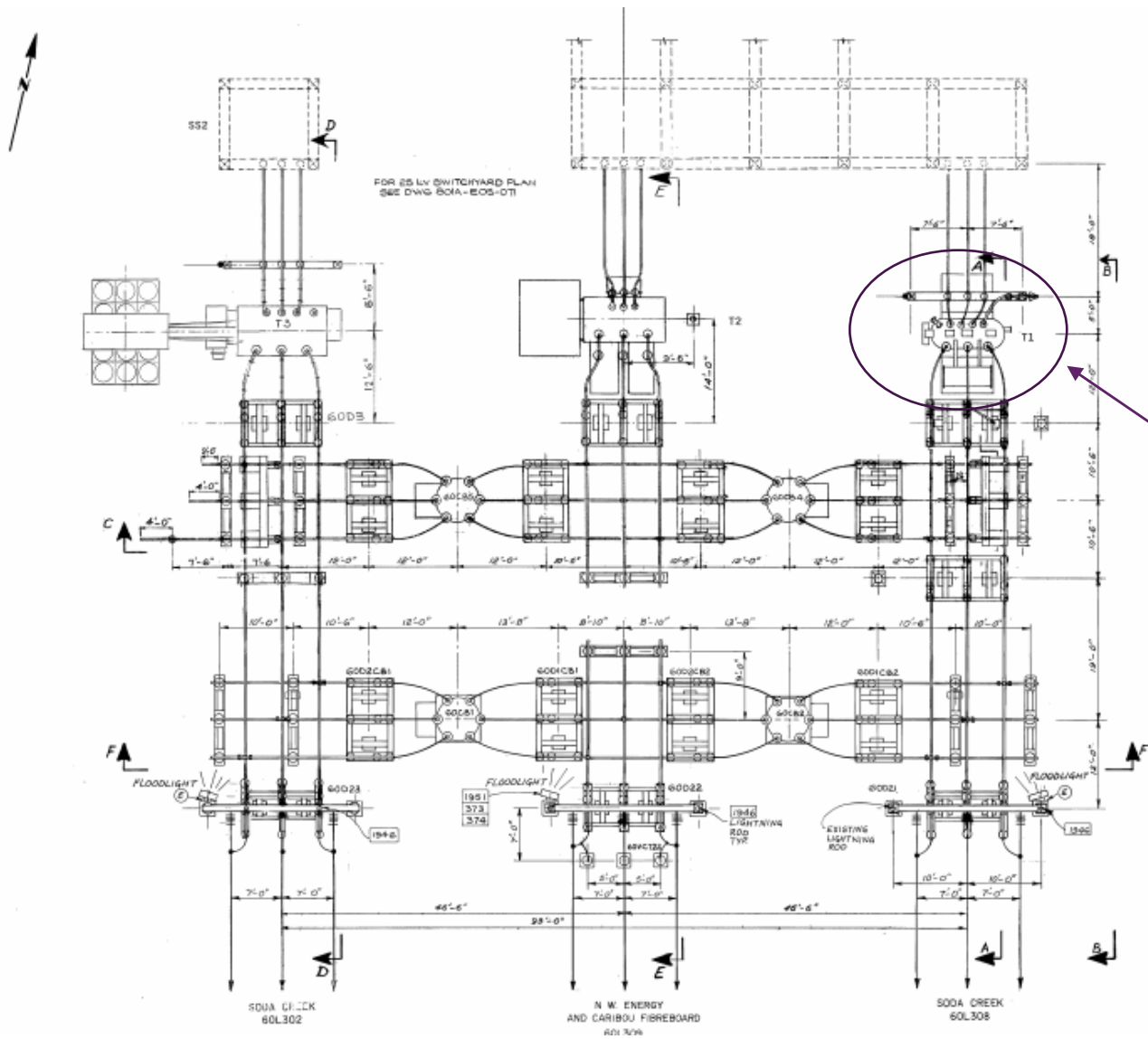




Case Study – Existing Station

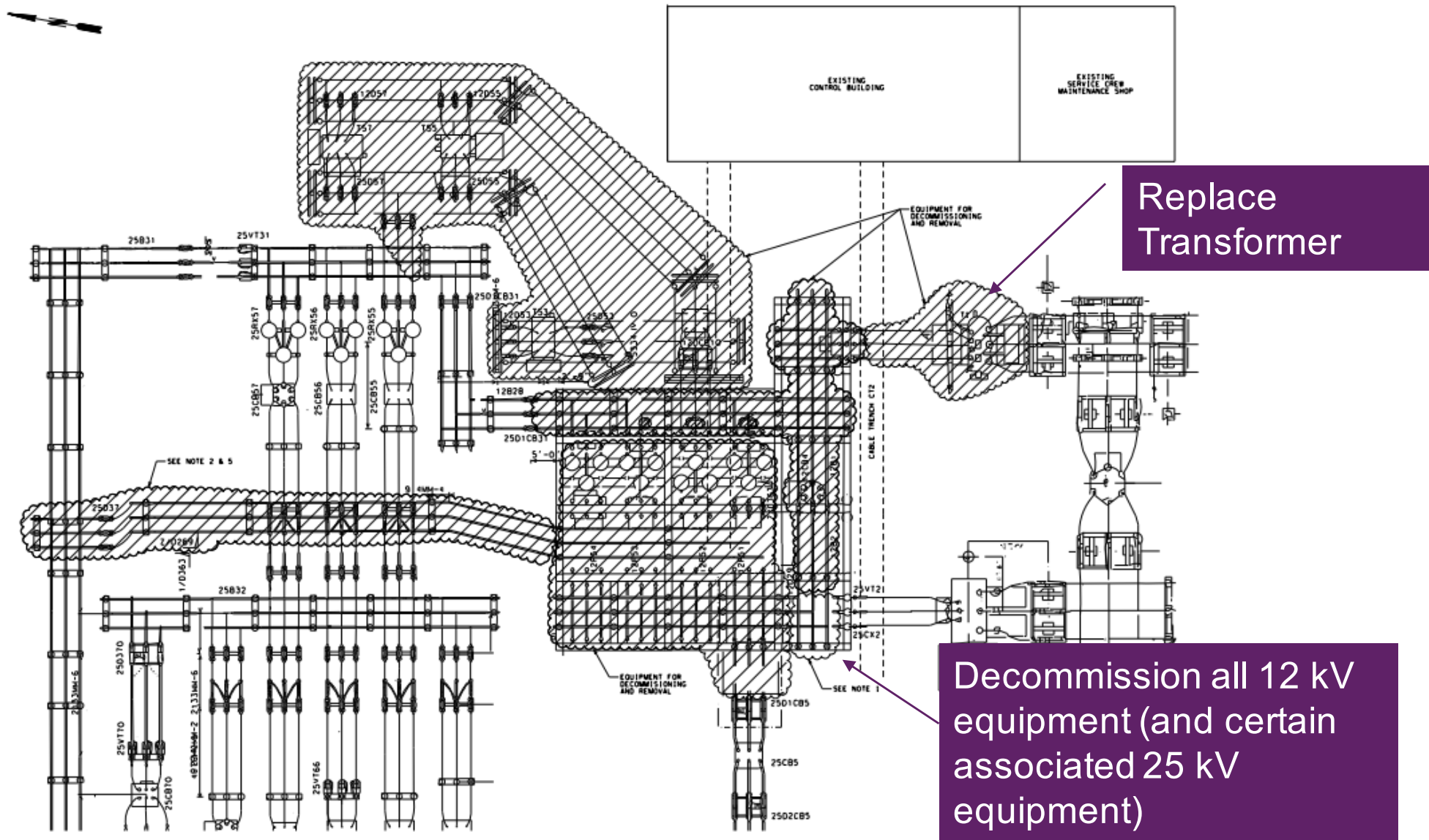
The load has now exceeded the station's firm capacity

T1 is a 60/12 kV transformer



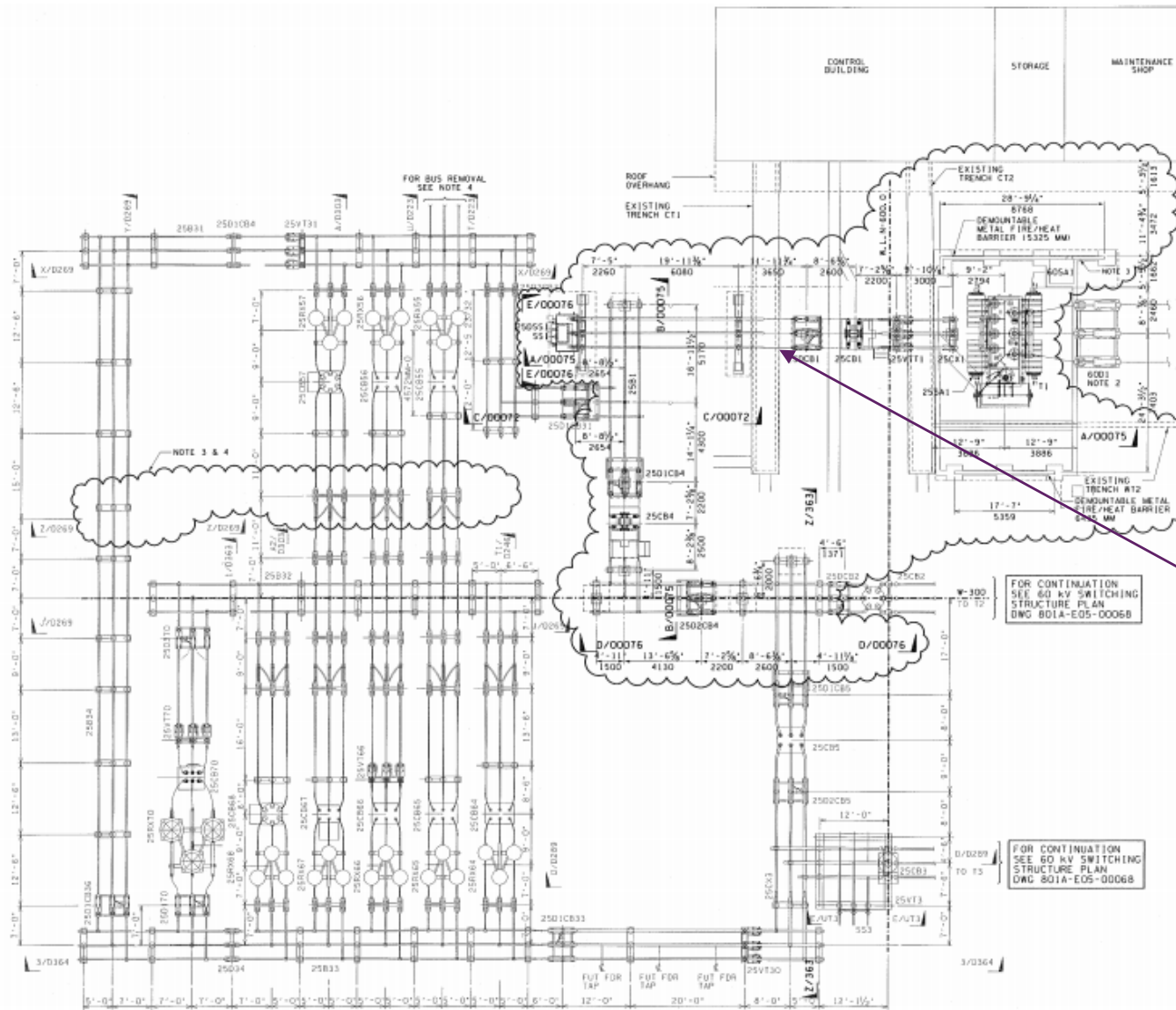


Case Study – Decommission





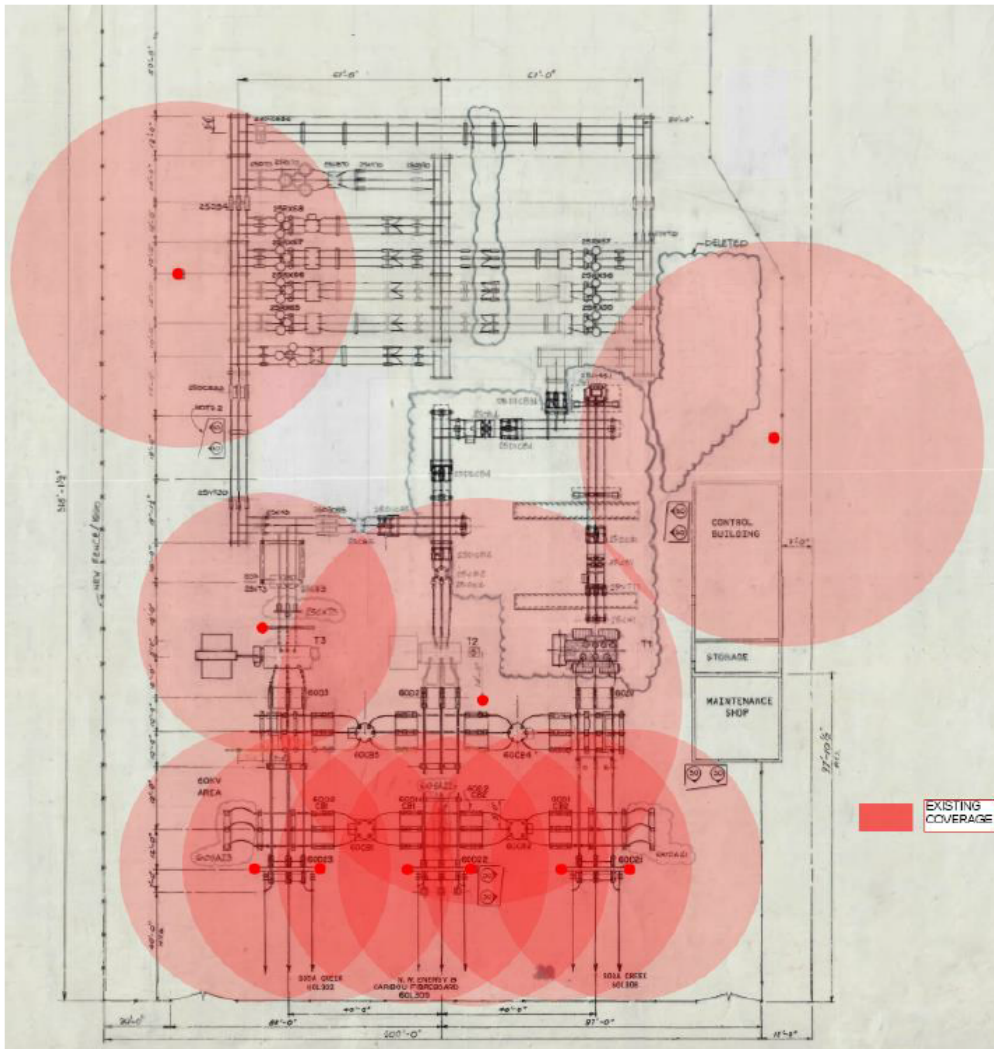
Case Study – Scope Addition



Also add new 25 kV busbars to replace 12 kV busbars



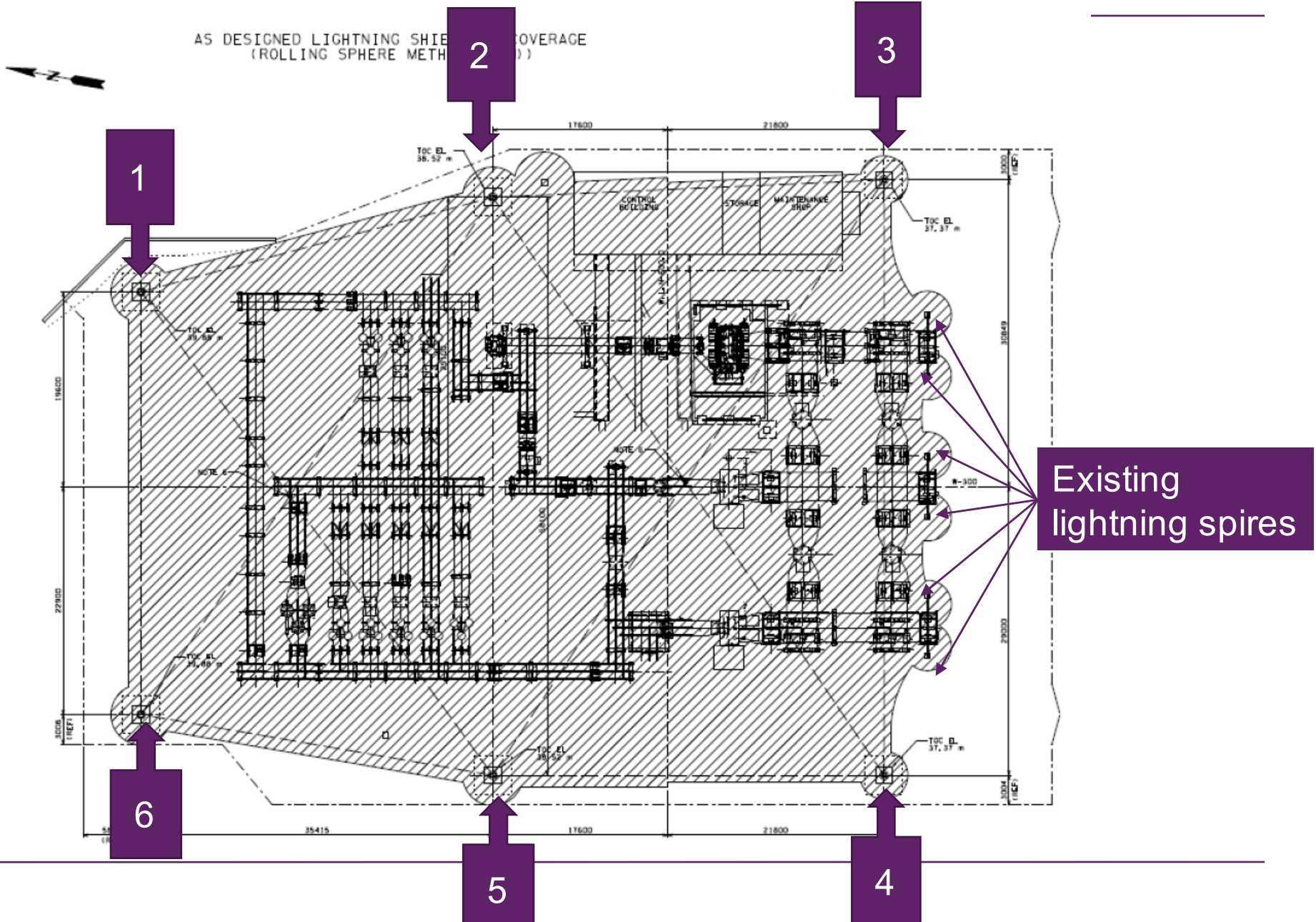
Case Study – Existing Lightning Shield Design



- No document about lightning protection.
- Location of lightning masts and spires was identified at site and on layout drawings.
- Assumed the station was protected by the fixed angle method.
- Shows the coverage by the fixed angle method if using existing masts and spires.

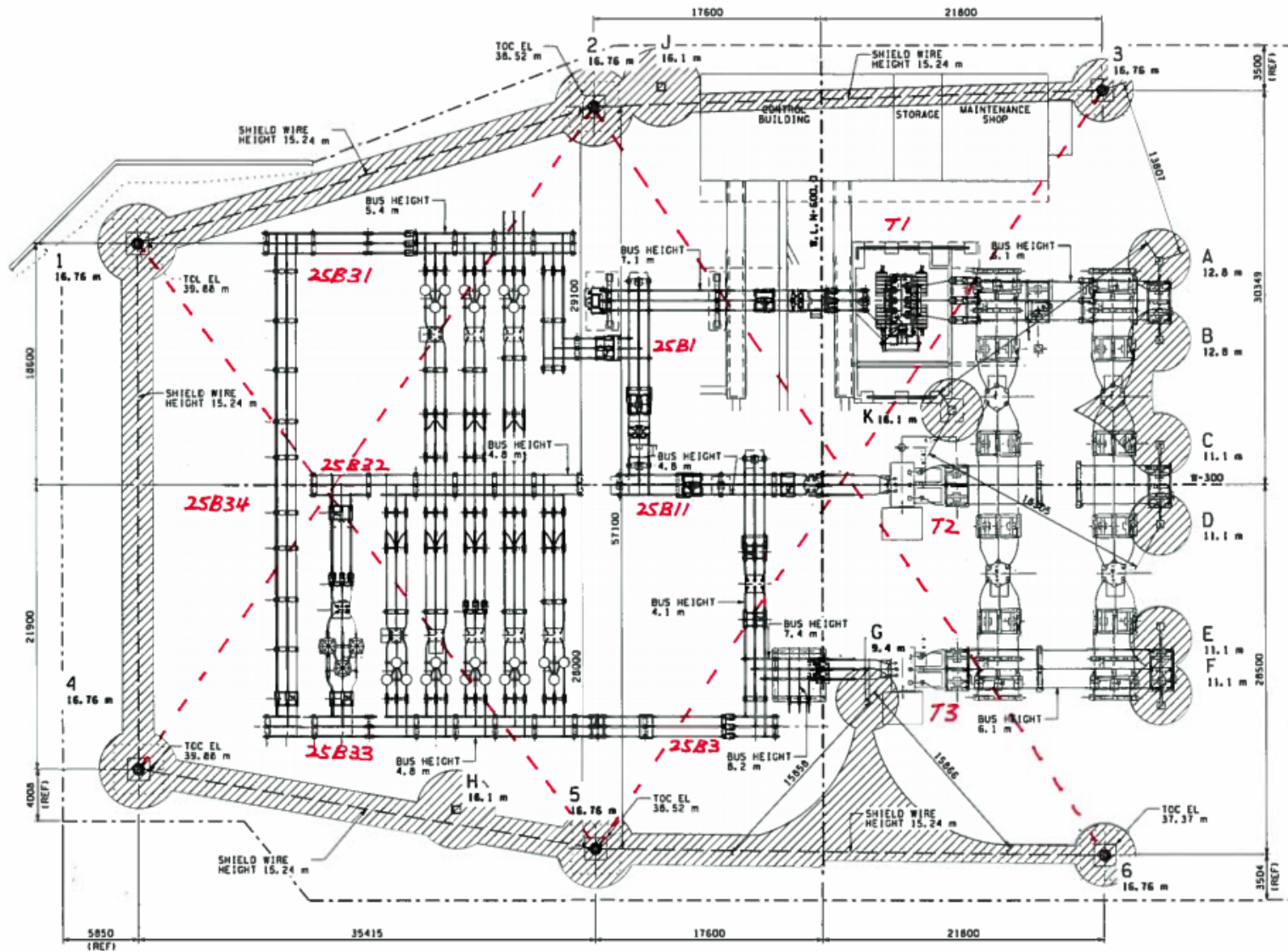


Case Study – New Lightning Shield Design



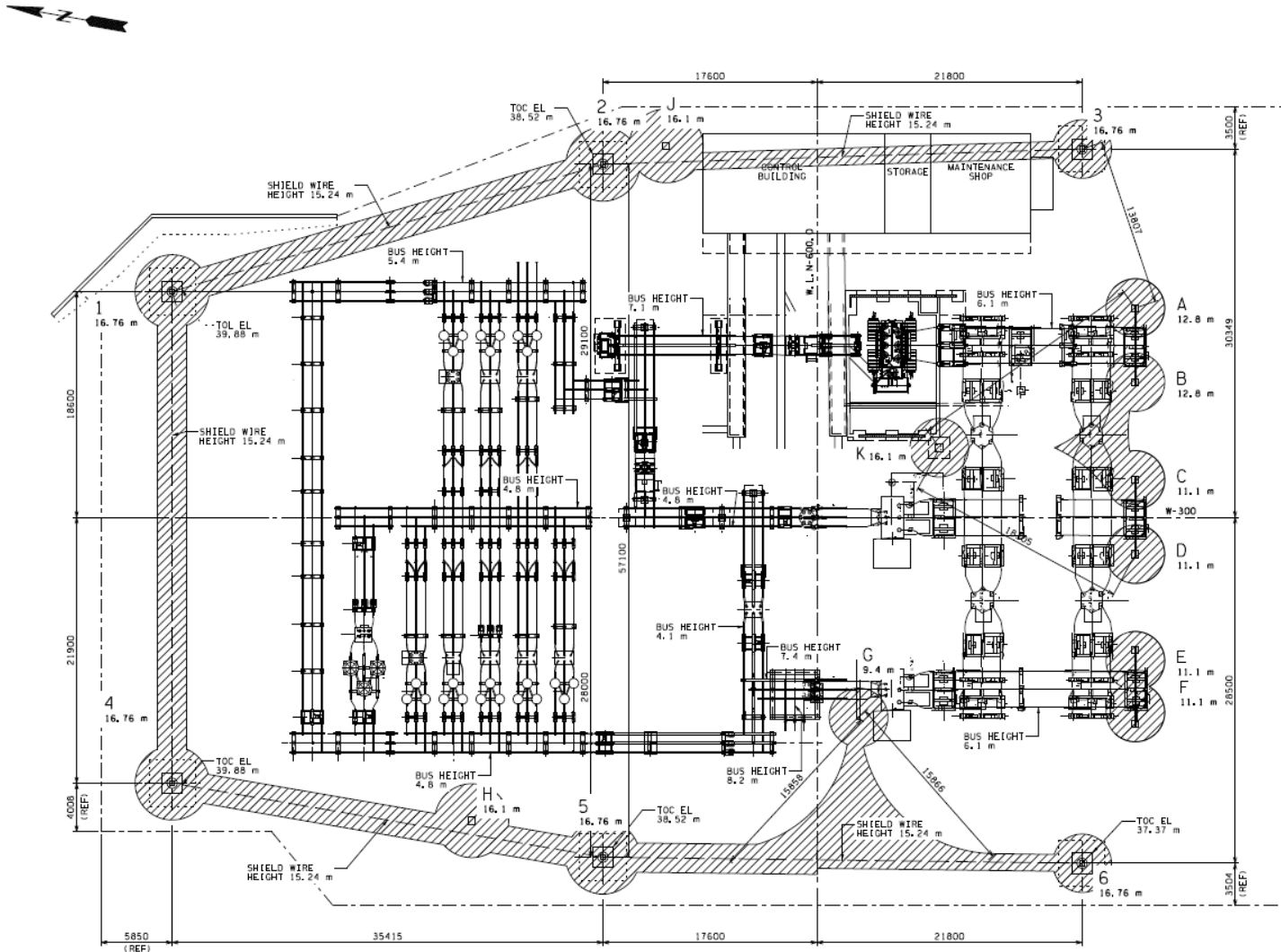


Case Study – Staging Plan



Case Study – Shielding Coverage Without Shield Wires

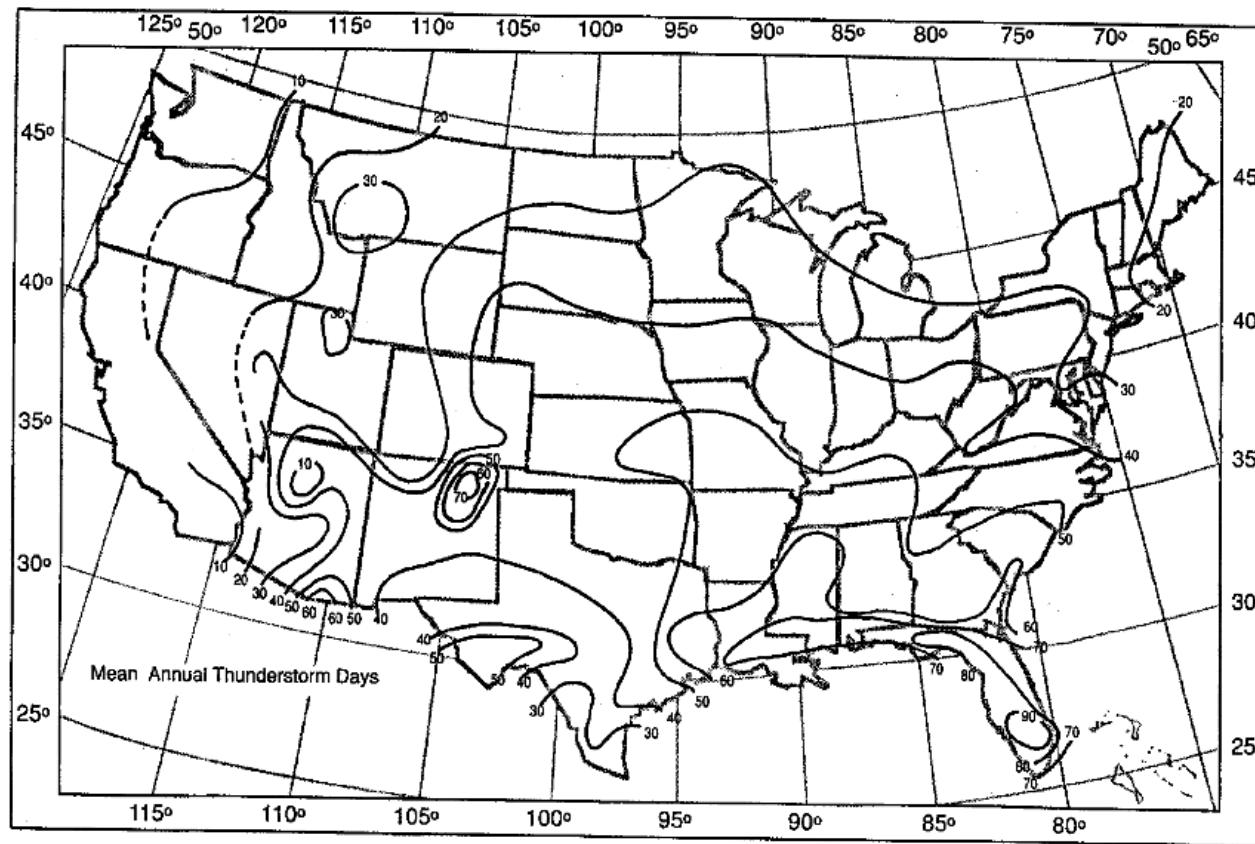
LIGHTNING SHIELDING COVERAGE AFTER SHIELD WIRE INSTALLATION
(ROLLING SPHERE METHOD (EGM))





Keraunic Level

The average annual number of thunderstorm days or hours for a given locality. A thunderstorm day is a day (24 hours) during which thunder has been heard at least once.



Ground Flash Density

Ground flash density (GFD) is defined as the average number of lightning strokes per unit area per unit time (year) at a particular location. It is usually assumed that the GFD to earth, a substation, or a transmission or distribution line is roughly proportional to the keraunic level at the locality.

Equation for GFD is

$$N_k = 0.12T_d$$

$$N_m = 0.31T_d$$

Where

N_k is the number of flashes to earth per square kilometer per year

N_m is the number of flashes to earth per square mile per year

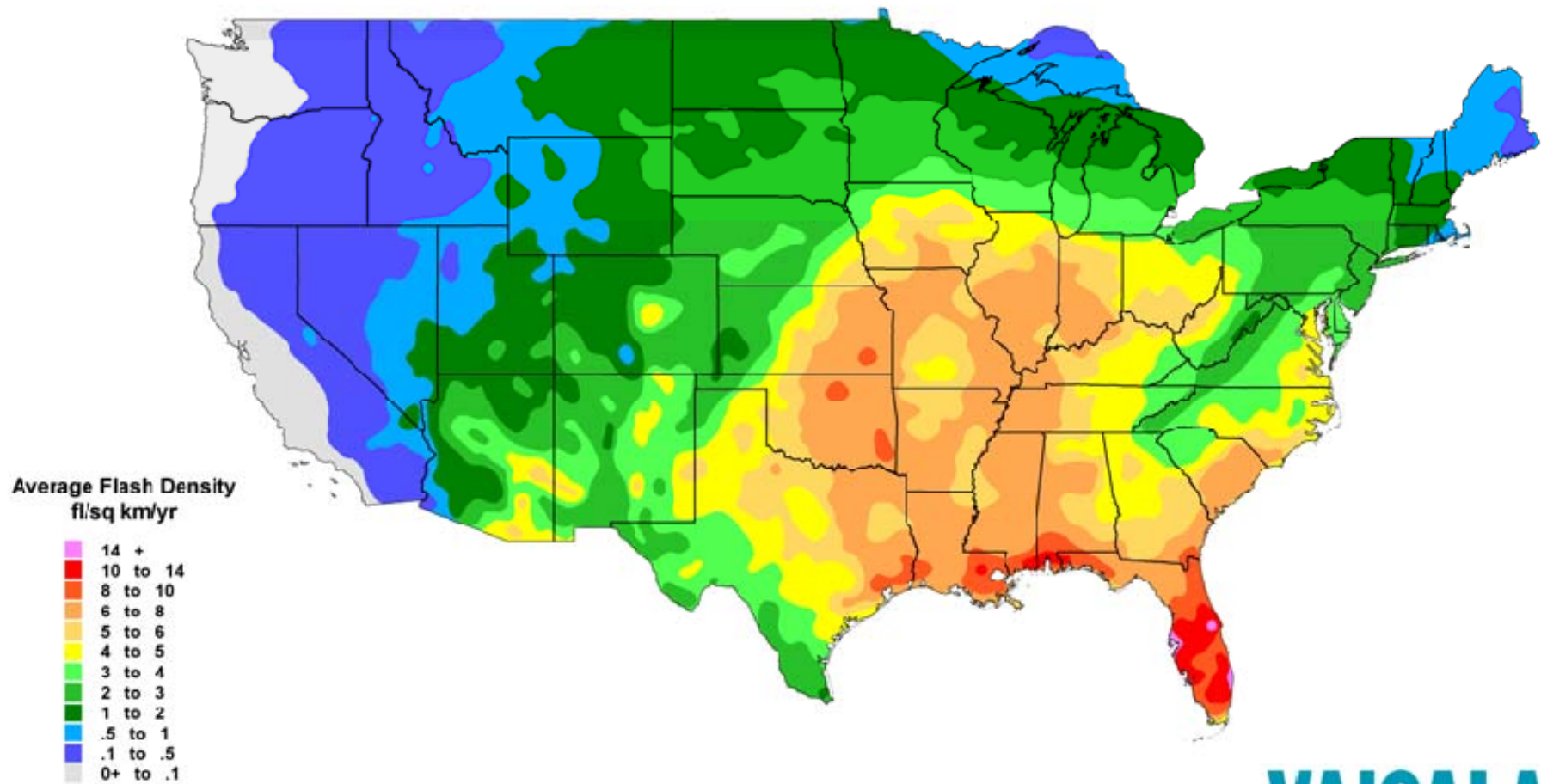
T_d is the average annual keraunic level, thunderstorm days



amec
foster
wheeler

Ground Flash Density

Vaisala's National Lightning Detection Network (NLDN)
Cloud-to-Ground Lightning Incidence in the Continental U.S. (1997 - 2010)



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Ground Flash Density

For Canadian cities, GFD information can also be found on Environment Canada
<https://ec.gc.ca/foudre-lightning/default.asp?lang=EN&n=4871AAE6-1>

British Columbia

Lightning Activitiy in British Columbia

City	Area in square kilometres	Total flashes (1999 to 2008)	Total flashes per square kilometre, per year	Cloud-to-Ground flashes (1999 to 2008)	Cloud-to-Ground flashes per square kilometre, per year
Cranbrook	14.19	60	0.42	52	0.37
Fort Nelson	5.52	22	0.40	19	0.34
Fort St. John	18.52	51	0.28	45	0.24
Prince George	28.09	66	0.23	59	0.21
Kelowna	54.78	71	0.13	59	0.11

Failure Rate for a Substation

There is no known method of providing 100% shielding.

There will always be a risk even if the station is fully shielded.

IEC Standard 62305-2 – 2010 identifies the tolerable risk R_T for a substation, where the risk level is affected by different type of losses.

Tolerable risk (R_T) for a substation is defined in L2, loss of service to the public

	Types of loss	R_T (y-1)
L1	Loss of human life or permanent injuries	10^{-5}
L2	Loss of service to the public	10^{-3}
L3	Loss of cultural heritage	10^{-4}
L4	Loss of economic value	Cost/benefit comparison

Failure Rate for a Substation

To calculate the failure rate (tolerable risk) of a substation, we need to know:

- GFD of the area
- The area of the station
- Failure rate of the station without shielding coverage
- Failure rate of the design method we apply

For our case study, failure rate of the station without shielding coverage is:

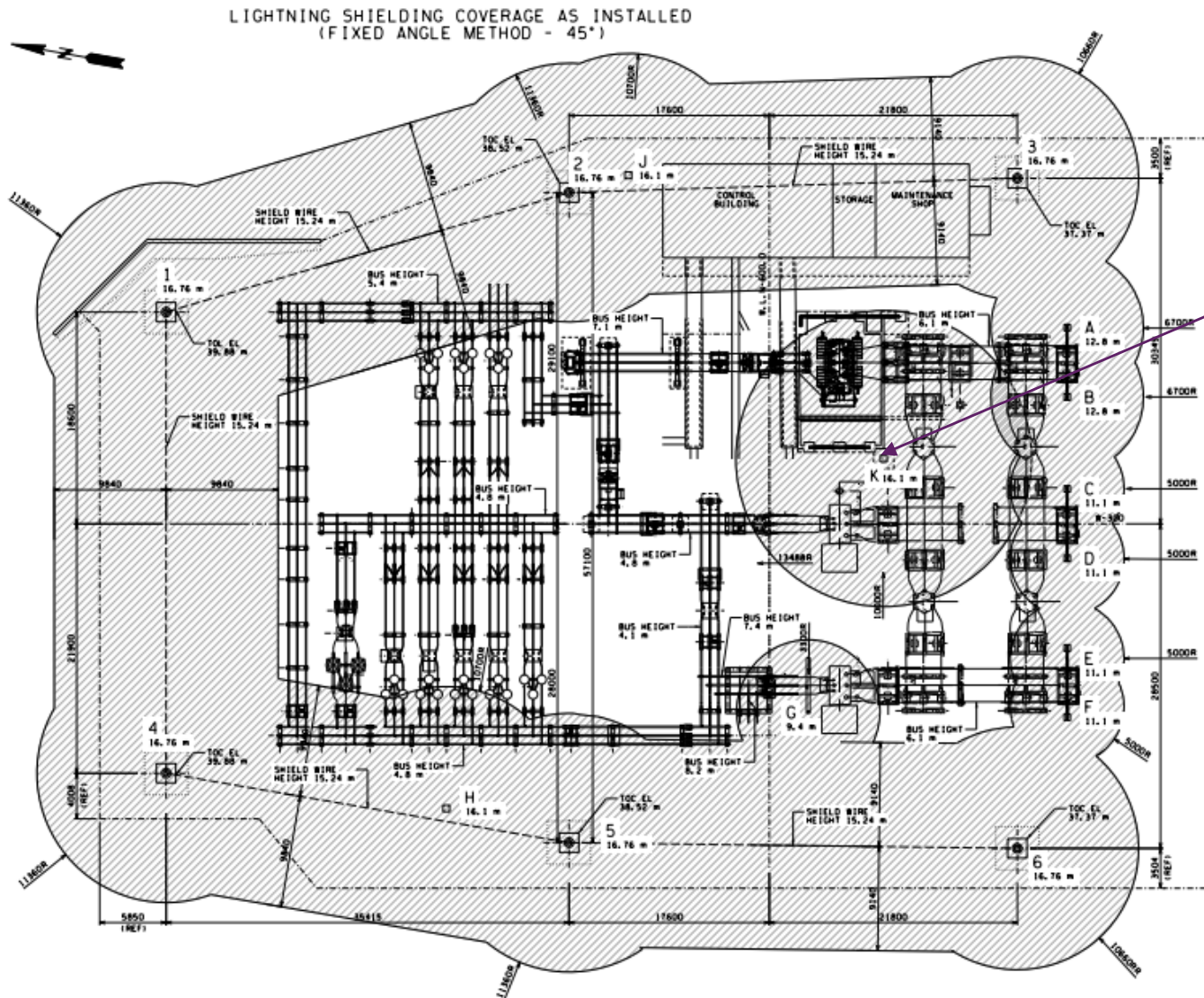
$$\begin{aligned} X &= 0.04 \text{ flashes/km}^2/\text{year} \times 0.002930 \text{ km}^2 \\ &= 1.17 \times 10^{-4} \text{ flashes/year or } 8,532 \text{ years between flashes} \end{aligned}$$

An example of using the rolling sphere method can reduce the failure rate to:

$$\begin{aligned} X &= 1.172 \times 10^{-4} \text{ flashes/year} \times 0.0005 \text{ (failure rate)} \\ &= 5.86 \times 10^{-8} \text{ flashes/year or } 17,064,846 \text{ years between flashes} \end{aligned}$$



Case Study (option 1)

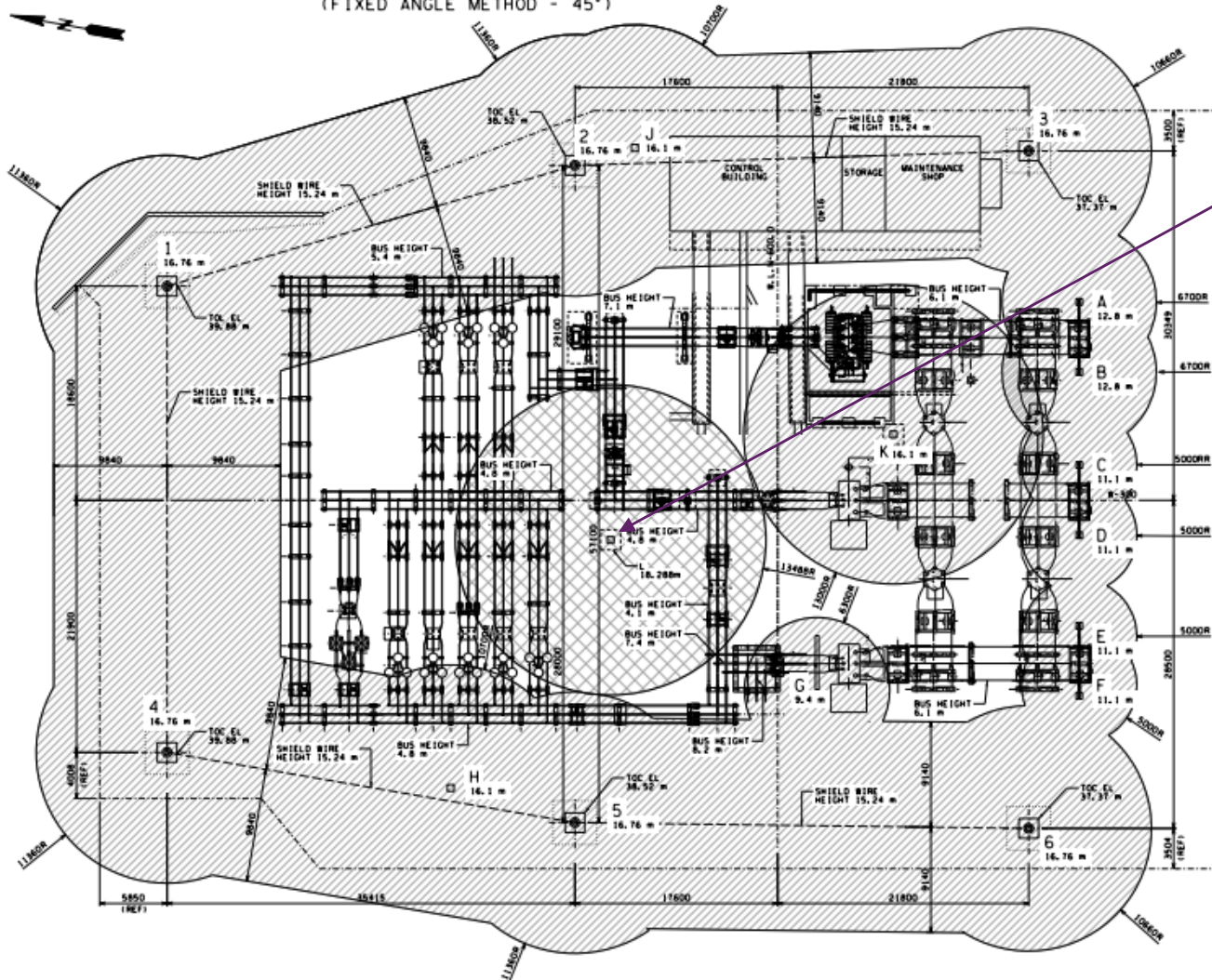


Replaced one lightning mast to provide shielding coverage to transformers



Case Study (option 2)

LIGHTNING SHIELDING COVERAGE AFTER SHIELD WIRE INSTALLATION
(FIXED ANGLE METHOD - 45°)



An additional lightning mast is added to increase shielding coverage

Failure Rate for a Substation (Fixed Angle Method)

To find out the failure rate of this station, we have to identify:

	Shielded Area (m ²)	Unshielded Area (m ²)
No additional lightning mast (Option 1)	1010	1920
One additional lightning mast (Option 2)	1581	1349

The failure rate will be:

The probability of the lightning stroke within the **shielded** area

OR

The probability of the lightning stroke within the **unshielded** area

Failure Rate for a Substation (Fixed Angle Method)

For Option 1

The probability of a stroke hitting the unshielded area is:

$$X = 0.04 \text{ flashes/km}^2/\text{year} \times 0.001920 \text{ km}^2$$

$$X = 7.68 \times 10^{-5} \text{ strokes/year}$$

The probability of a stroke hitting the shielded area is:

$$X = 0.04 \text{ flashes/km}^2/\text{year} \times 0.001010 \text{ km}^2 \times 0.002 \text{ (failure rate of fixed angle method)}$$

$$X = 8.1 \times 10^{-8} \text{ strokes/year}$$

Combining these probabilities, we have:

$$\text{Failure rate} = 7.68 \times 10^{-5} + 8.1 \times 10^{-8} = 7.69 \times 10^{-5} \text{ flashes/year or 13,004 years between flashes}$$

Failure Rate for a Substation (Fixed Angle Method)

For Option 2

The probability of a stroke hitting the unshielded area is:

$$X = 0.04 \text{ flashes/km}^2/\text{year} \times 0.001349 \text{ km}^2$$

$$X = 5.396 \times 10^{-5} \text{ strokes/year}$$

The probability of a stroke hitting the shielded area is:

$$X = 0.04 \text{ flashes/km}^2/\text{year} \times 0.001581 \text{ km}^2 \times 0.002 \text{ (failure rate of fixed angle method)}$$

$$X = 1.265 \times 10^{-7} \text{ strokes/year}$$

Combining these probabilities, we have:

$$\text{Failure rate} = 5.396 \times 10^{-5} + 1.265 \times 10^{-7} = 5.41 \times 10^{-5} \text{ flashes/year or 18,489 years between flahses}$$

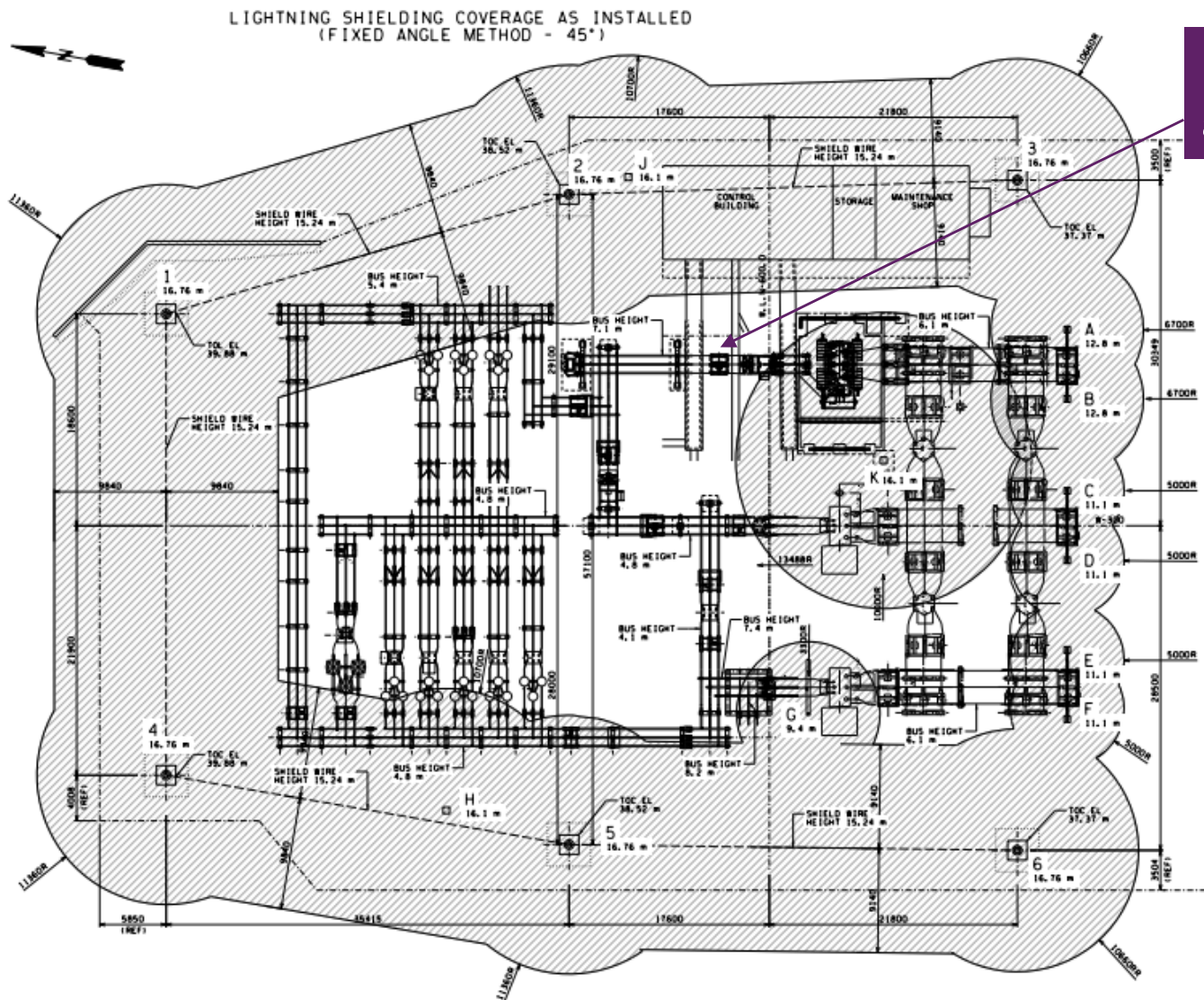
Failure Rate for a Substation (Comparison)

- Comparison of failure rates for various protection methods

Method	Failure Rate (y^{-1})
IEC 62305-2 L2	10^{-3}
Lightning Protection – Rolling Sphere Method	5.86×10^{-8}
Lightning Protection – Fixed Angle Method, Option 1	7.69×10^{-5}
Lightning Protection – Fixed Angle Method, Option 2	5.41×10^{-5}

- Use of the rolling sphere method and the fixed angle method all have failure rates that are several magnitude lower than IEC requirement

Consequences of Outages in the Event of a Lightning Stroke



Main 25 kV bus area is exposed

Conclusions

- A real case study for a substation built in BC Central Interior
- Highlights the importance of preparing the construction staging plan in the early stages of projects
- Fixed angle method sometimes is a more practical approach where existing facility are located in areas with low incidence of lightning strokes