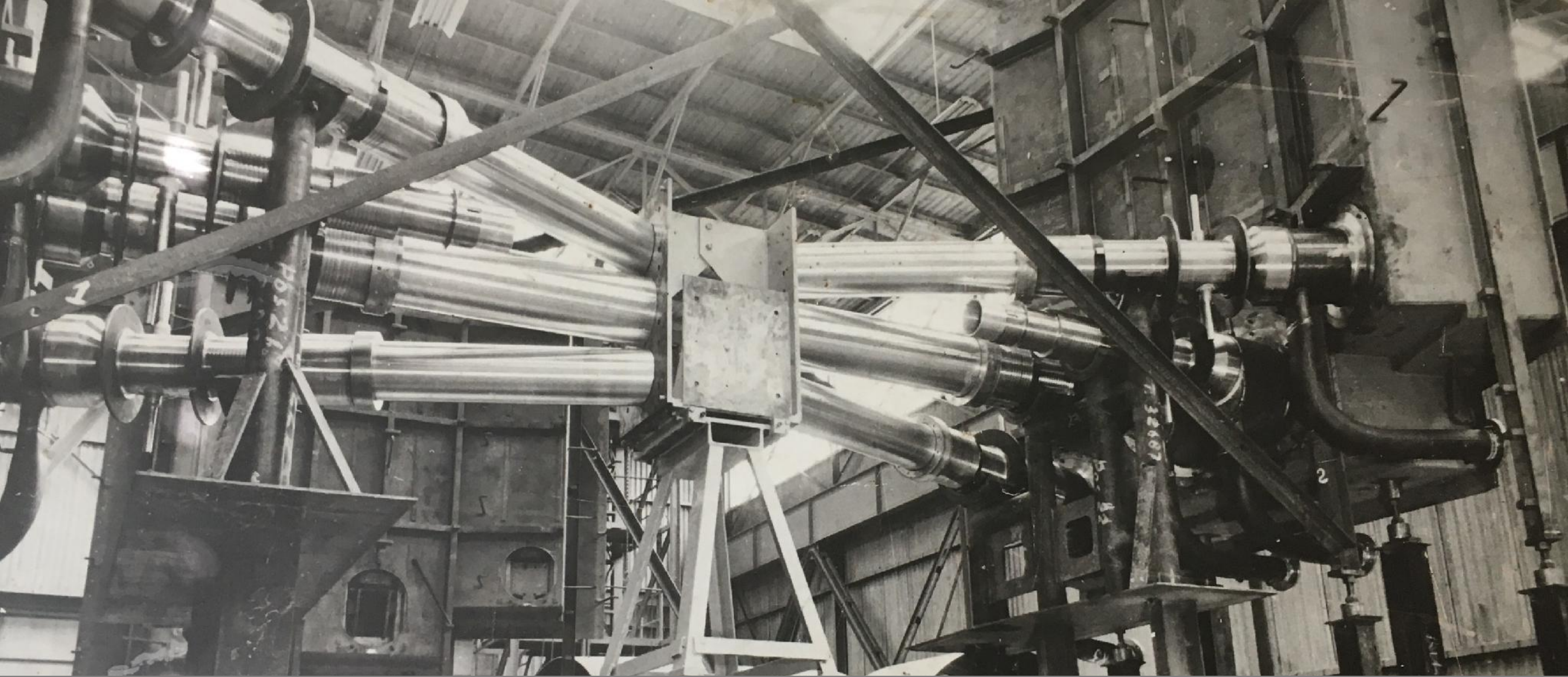


TU Delft Reactor Institute

Ageing management

Evaluating beam tube corrosion

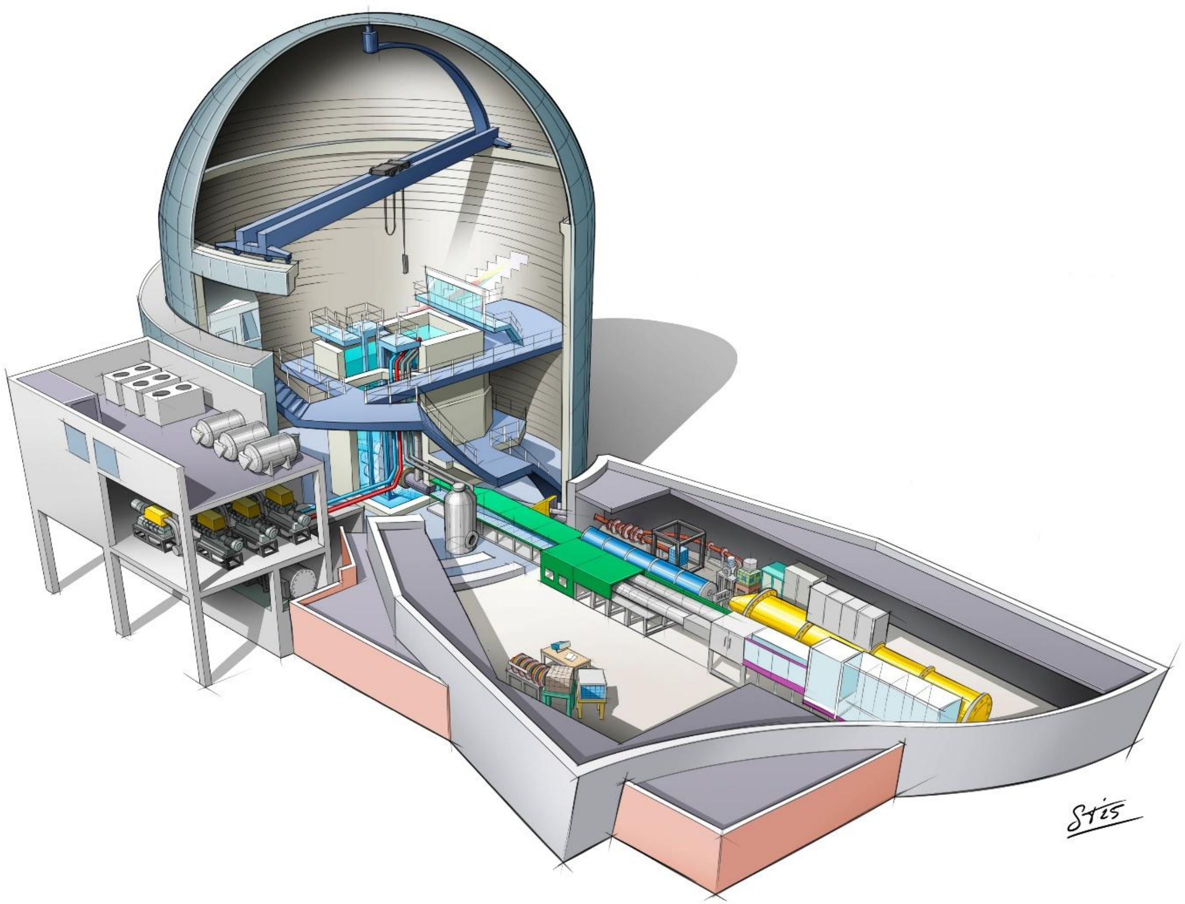
by Joeri Tober

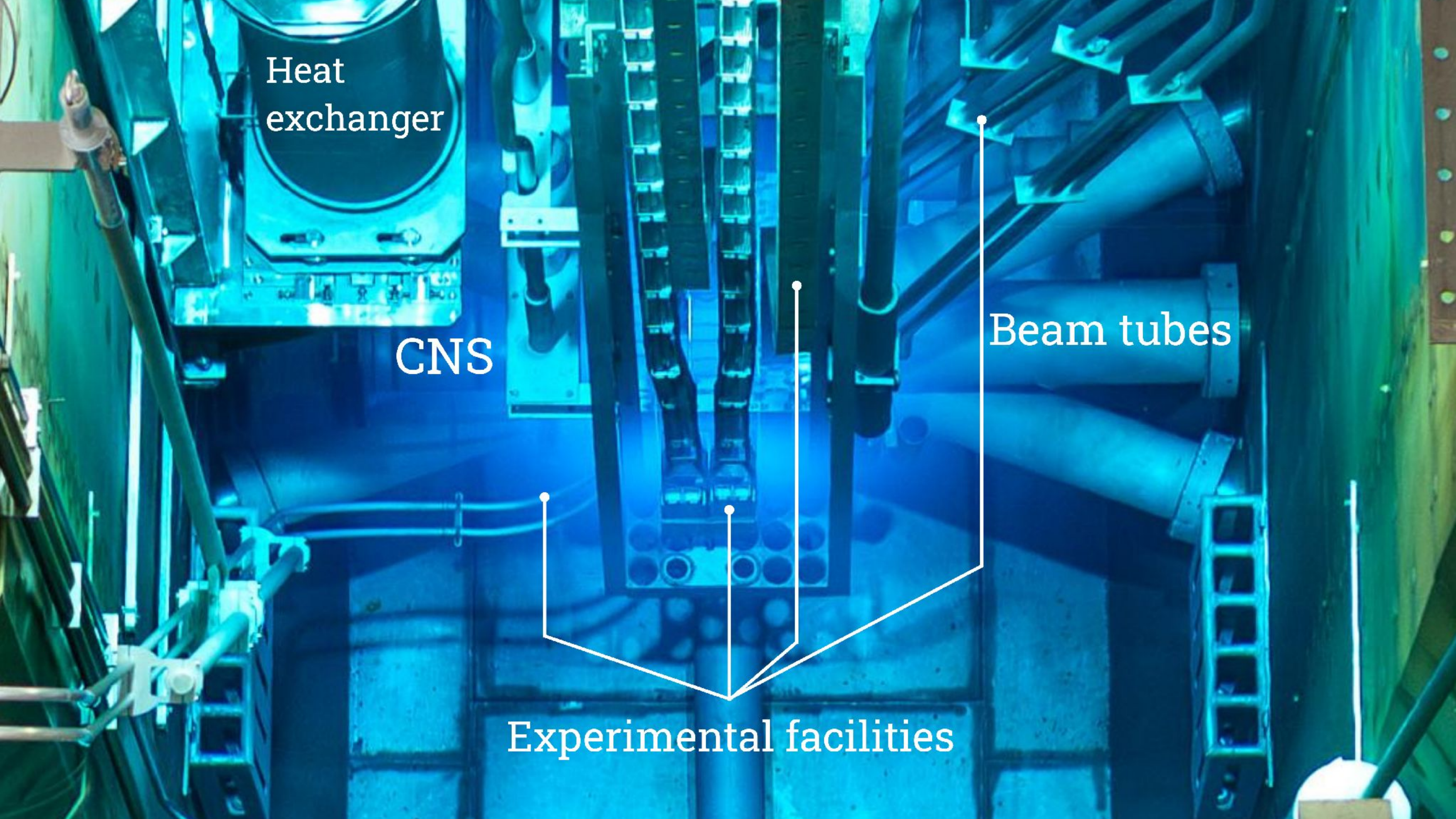
Introduction

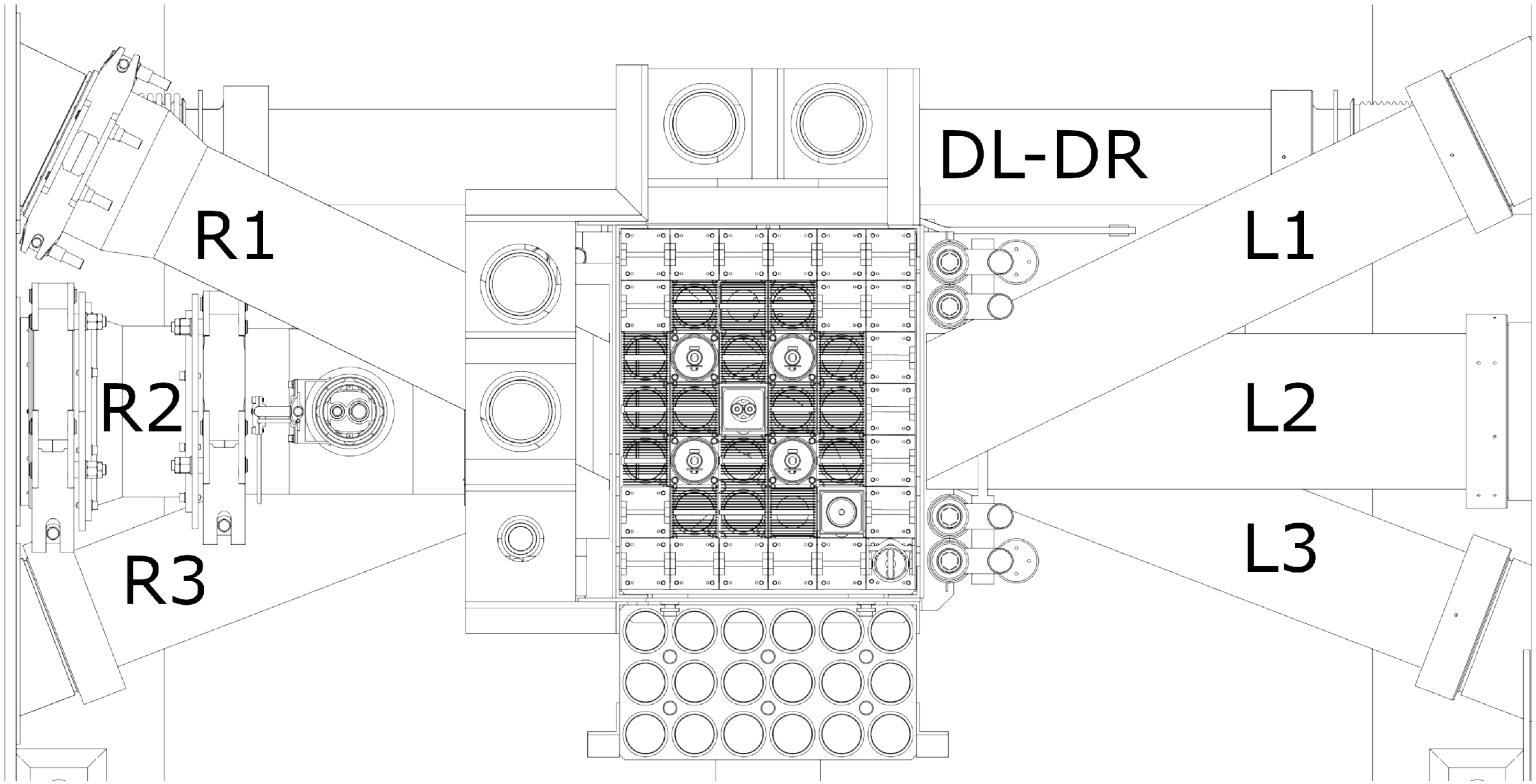
TU Delft Reactor Institute

Higher Education Reactor
In Dutch *Hoger Onderwijs Reactor = HOR:*

- 2,3 MWth open pool reactor
- to produce neutrons and positrons for research purposes
- in operation since 1963 (> 60 yrs)
- cold neutron source (CNS) in operation since 2024



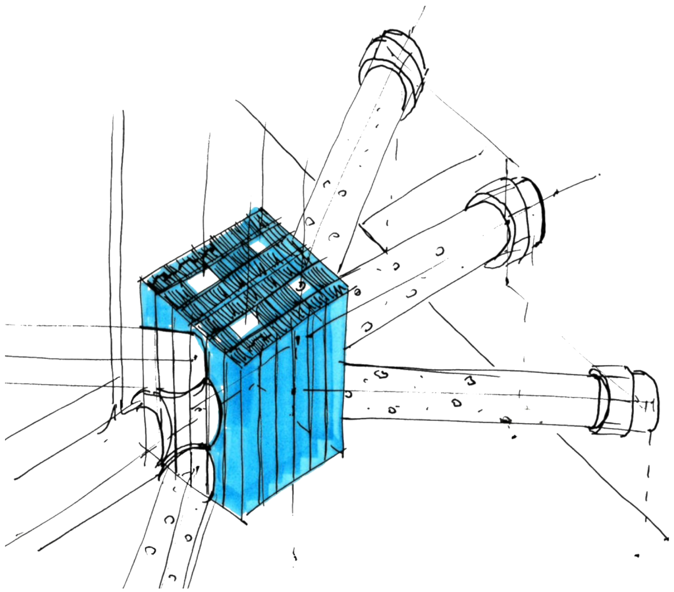

Heat exchanger
CNS
Beam tubes
Experimental facilities



The HOR has 7 beam tubes:

- All made of aluminum
- 2 recently replaced (R1, R2) to install the CNS
- Typical diameter ~25 cm, wall thickness of 5 mm
- 5 originals (L1, L2, L3, DL-DR and R3)

Beam tube inspection



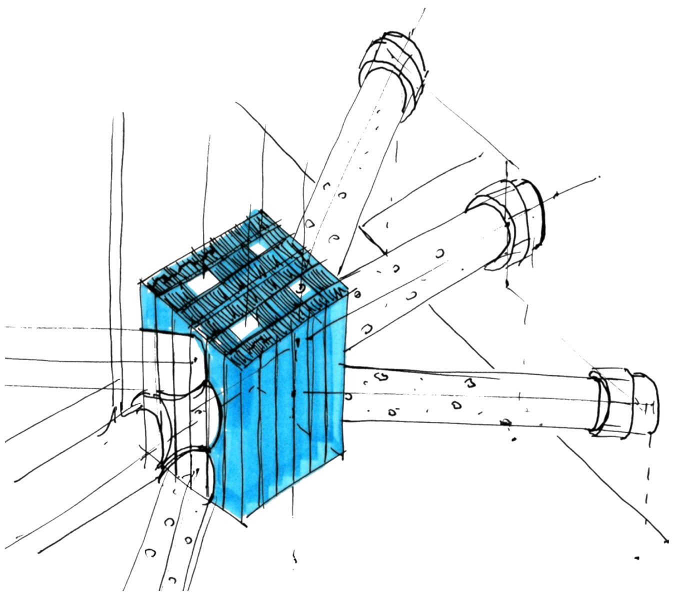
Beam tube inspection

Quantifying corrosion spots of beam tube L3.

Performed by NRG Arnhem, in 2021 and 2024.

In 2021 my colleague Alex coordinated this.

In 2024 I did, while Alex shared his lessons learned.



Beam tube inspection

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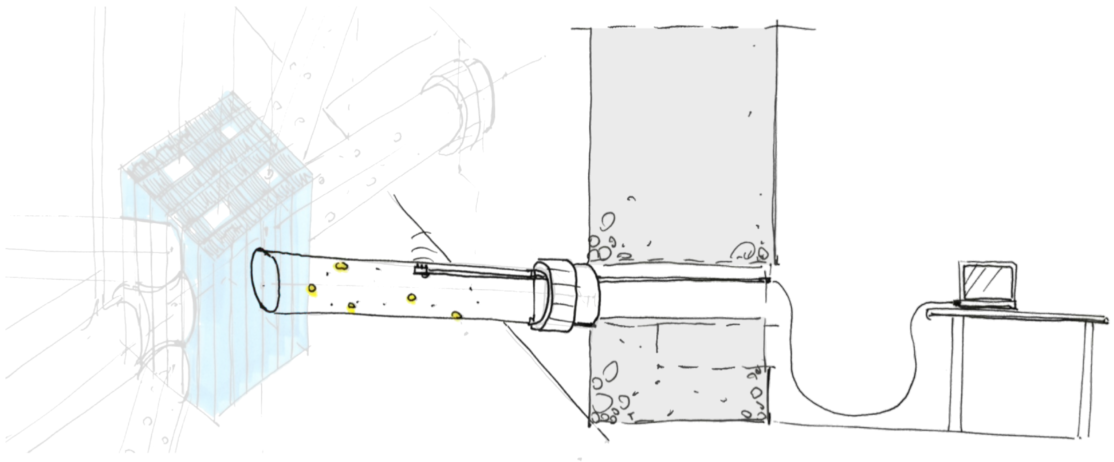
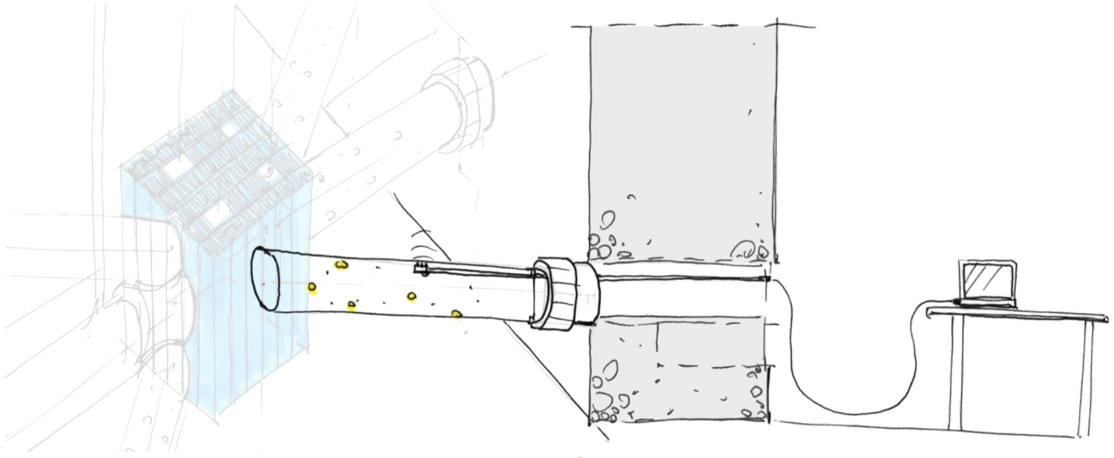
Technique: Ultrasonic Thickness (UT) measurements



Question 1

Still safe regarding *structural integrity*?



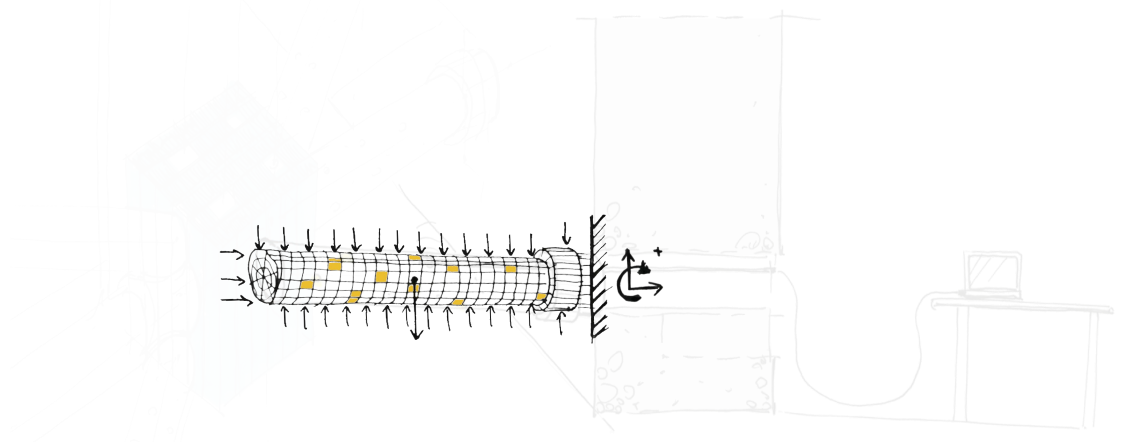
Question 1

Still safe regarding *structural integrity*?

This we let NRG Petten decide.

They performed a FEM analysis to evaluate L3 on:

- *strength* (tensile and combined stresses)
- *stiffness* (buckling stability)



Question 1

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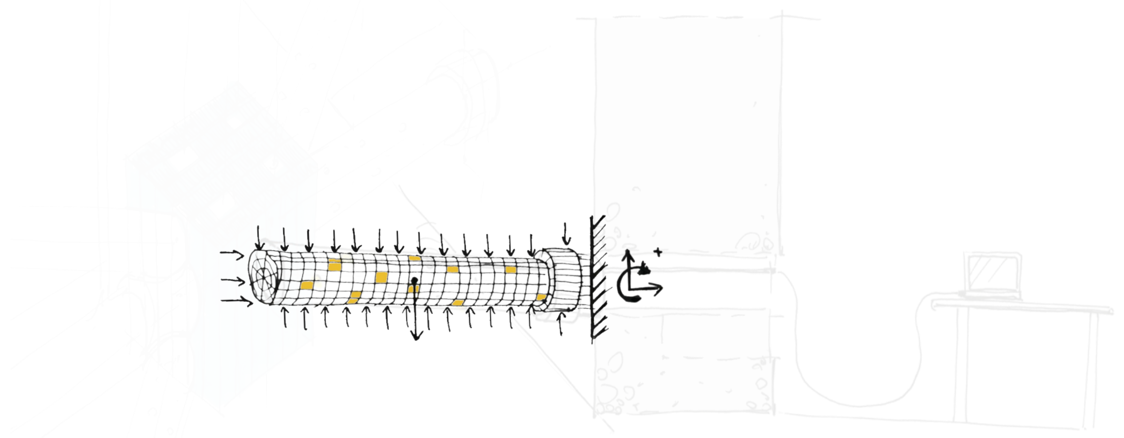
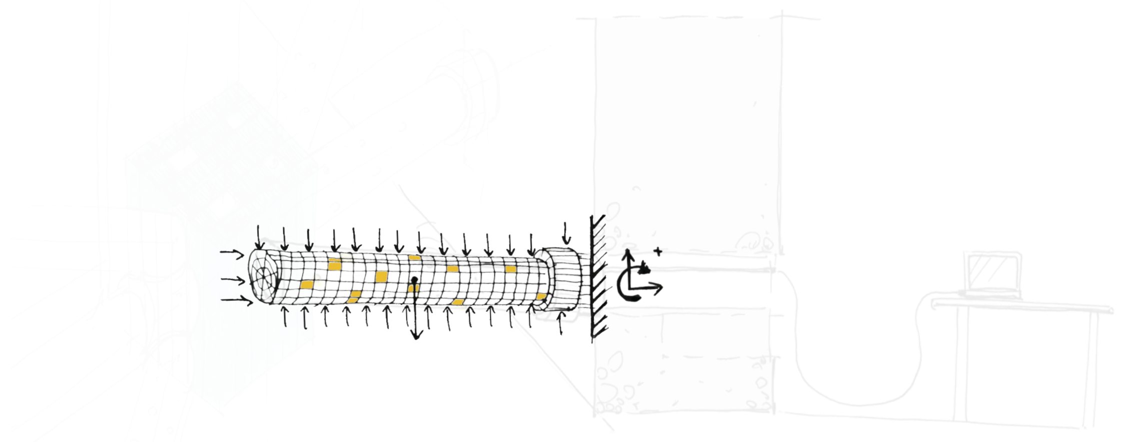


Yes, L3 with some corrosion spots is strong and stiff enough.

Question 2

Effect of *increasing* corrosion on strength and stiffness?

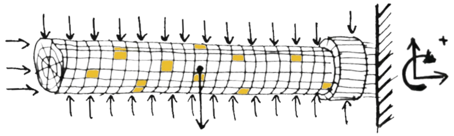


Question 2

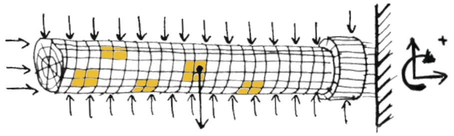
Effect of *increasing* corrosion on strength and stiffness?

NRG Petten also included a sensitivity analysis:

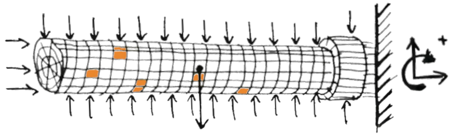
- by increasing *corrosion surface area* and *pit depth*
- evaluating again strength and stiffness
- and determining the safety margin



Case A



Case B



Case C

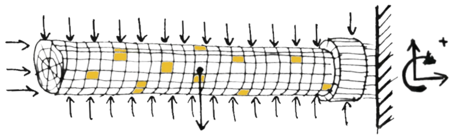
Question 2

Effect of *increasing* corrosion on strength and stiffness?

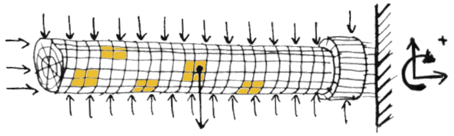
NRG Petten also included a sensitivity analysis:

- by increasing *corrosion surface area* and *pit depth*
- evaluating again strength and stiffness
- and determining the safety margin

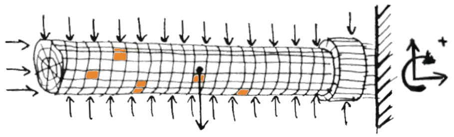
A combined increase of *corrosion surface area* (x 4) and the *pit depth* (x 1,7) results in a safety margin of 1,5.



Case A



Case B



Case C

Question 3

How to evaluate future thickness measurements?

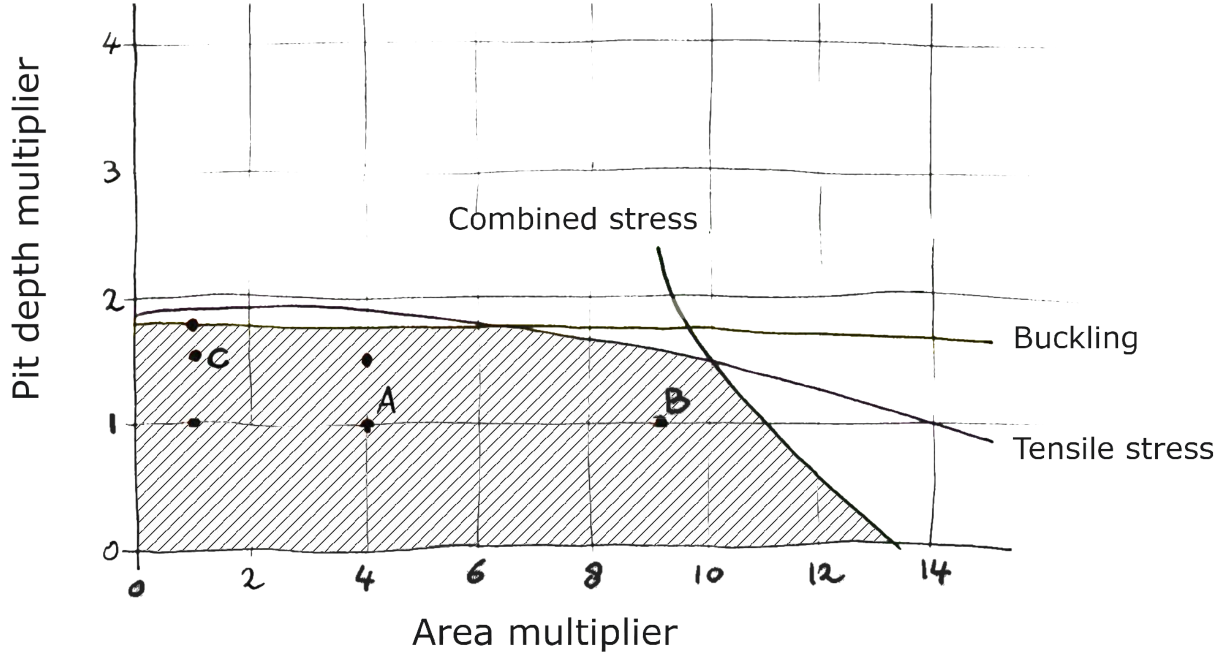
Question 3

How to evaluate future thickness measurements?

The safety margins (z) expressed in terms of

- corrosion surface area multiplier (x)
- corrosion pit depth multiplier (y)
- were set equal to 1,5, relating x and y.

In the y(x) plane this results in a region bounded by the safety margins z = 1,5.



Conclusion

Past measurements

Corrosion spots

↓

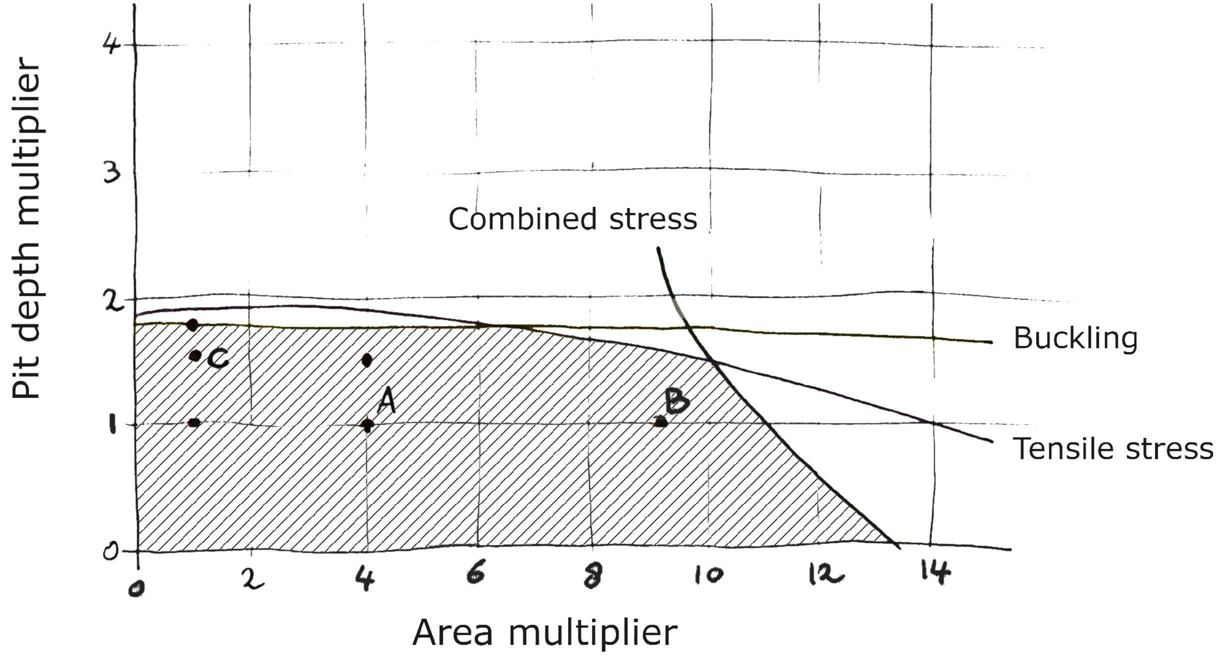
Quantification
with UT measurements

↓

Modelling and evaluation
with FEM model

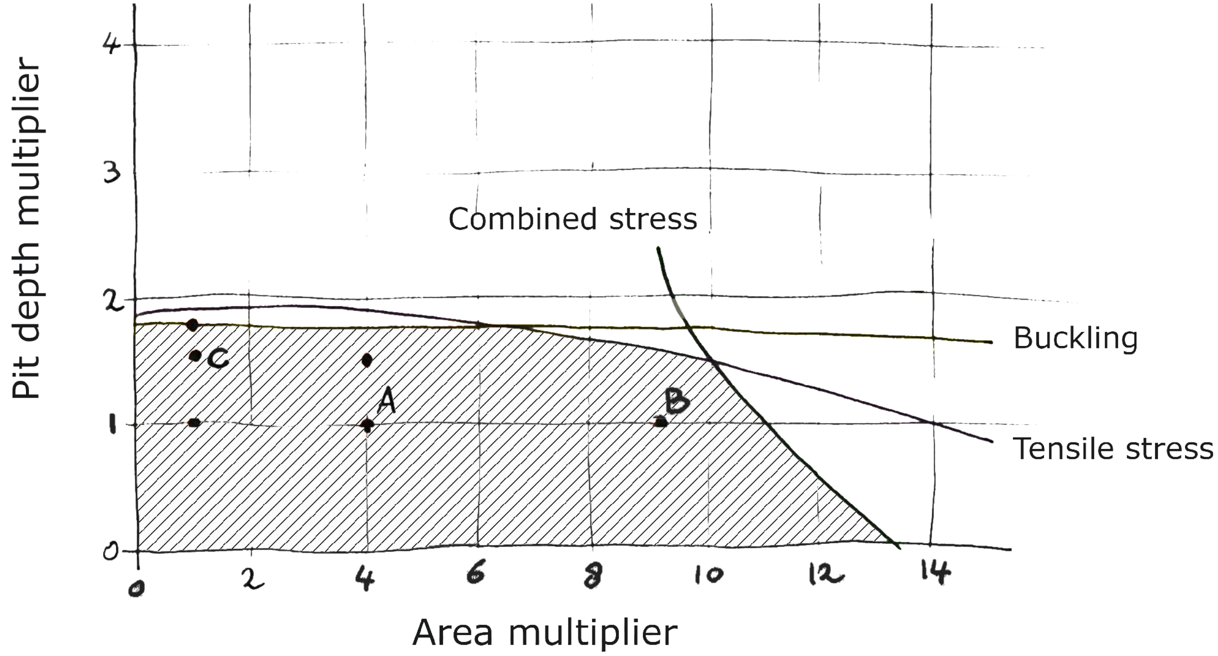
↓

Extending evaluation
with safety margin plot

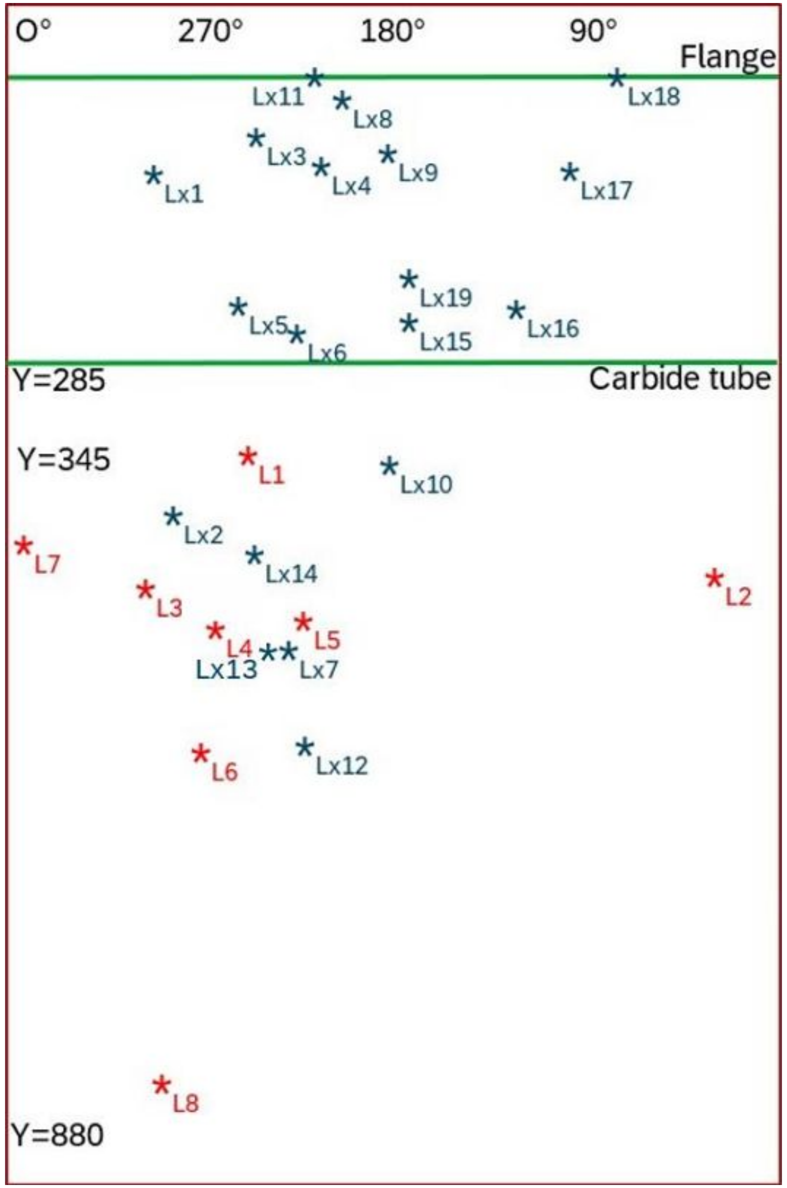


Conclusion

Past measurements	**Future measurements**
Corrosion spots	Corrosion spots
↓	↓
Quantification with UT measurements	Quantification with UT measurements
↓	↓
Modelling and evaluation with FEM model	
↓	
Extending evaluation with safety margin plot	Evaluation with safety margin plot



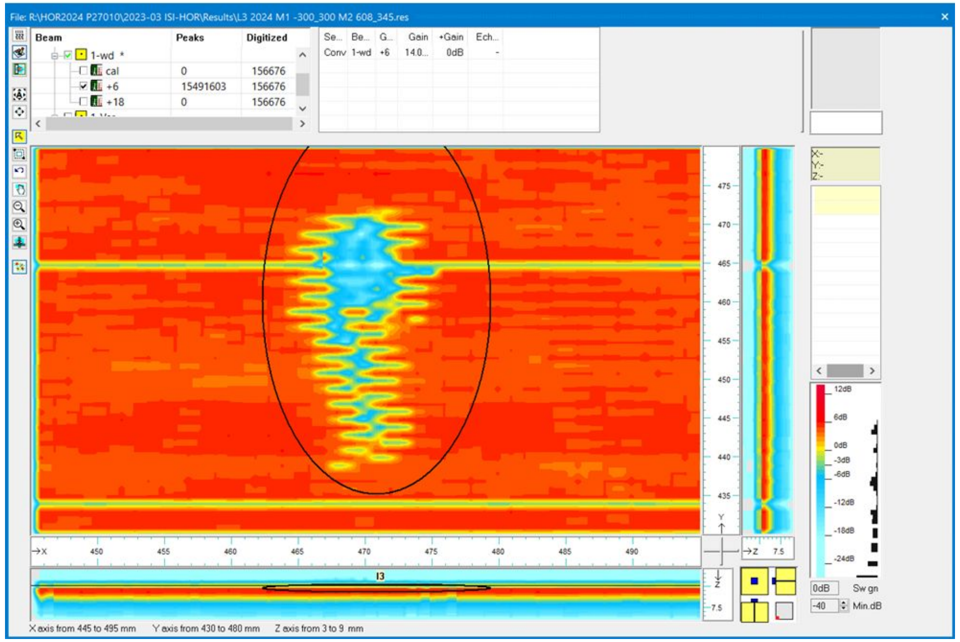
UT measurements



UT measurement results

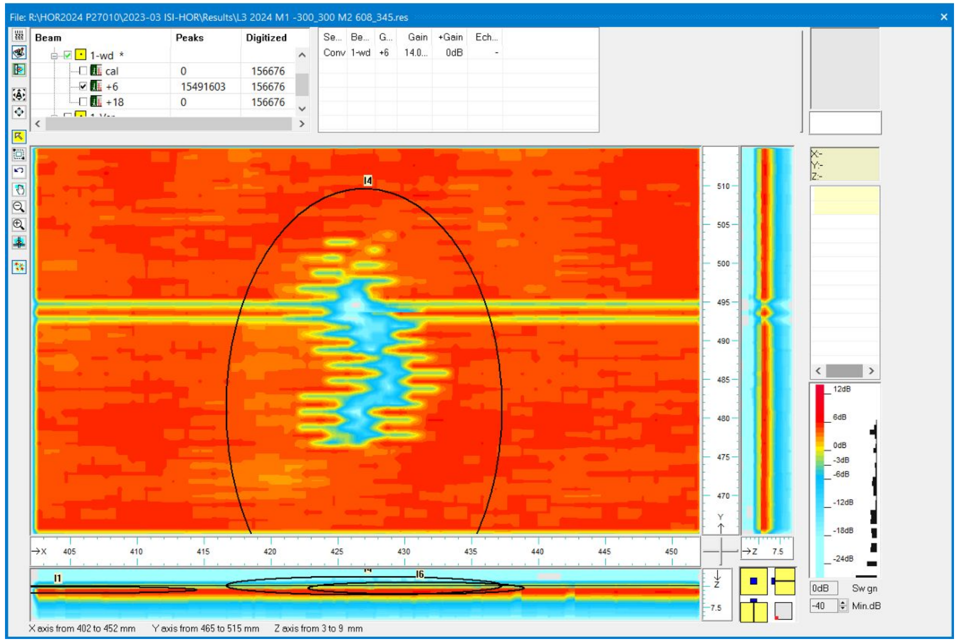
2024 Visual inspection position 290°

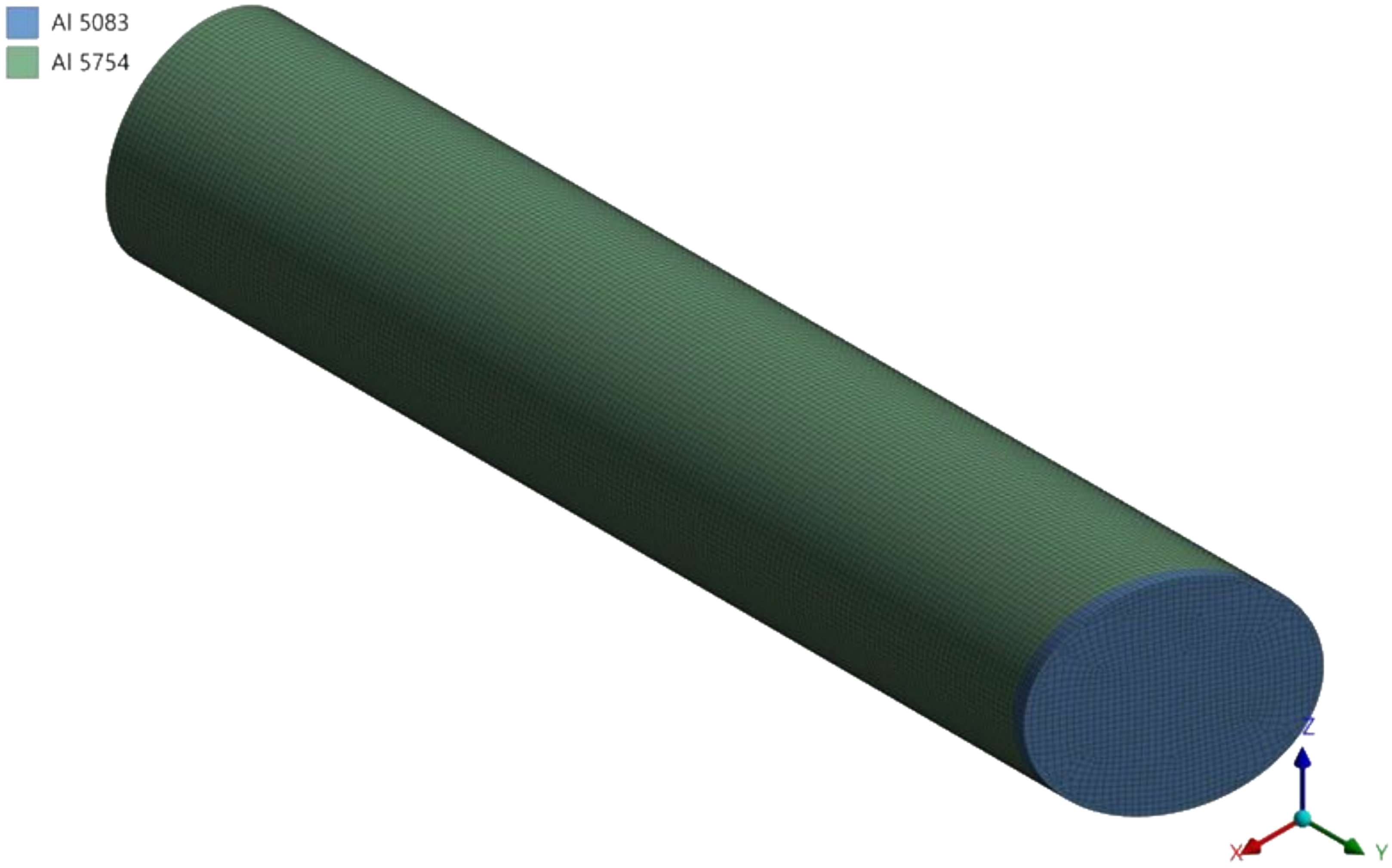
2024 BCD View Isotropic Scale



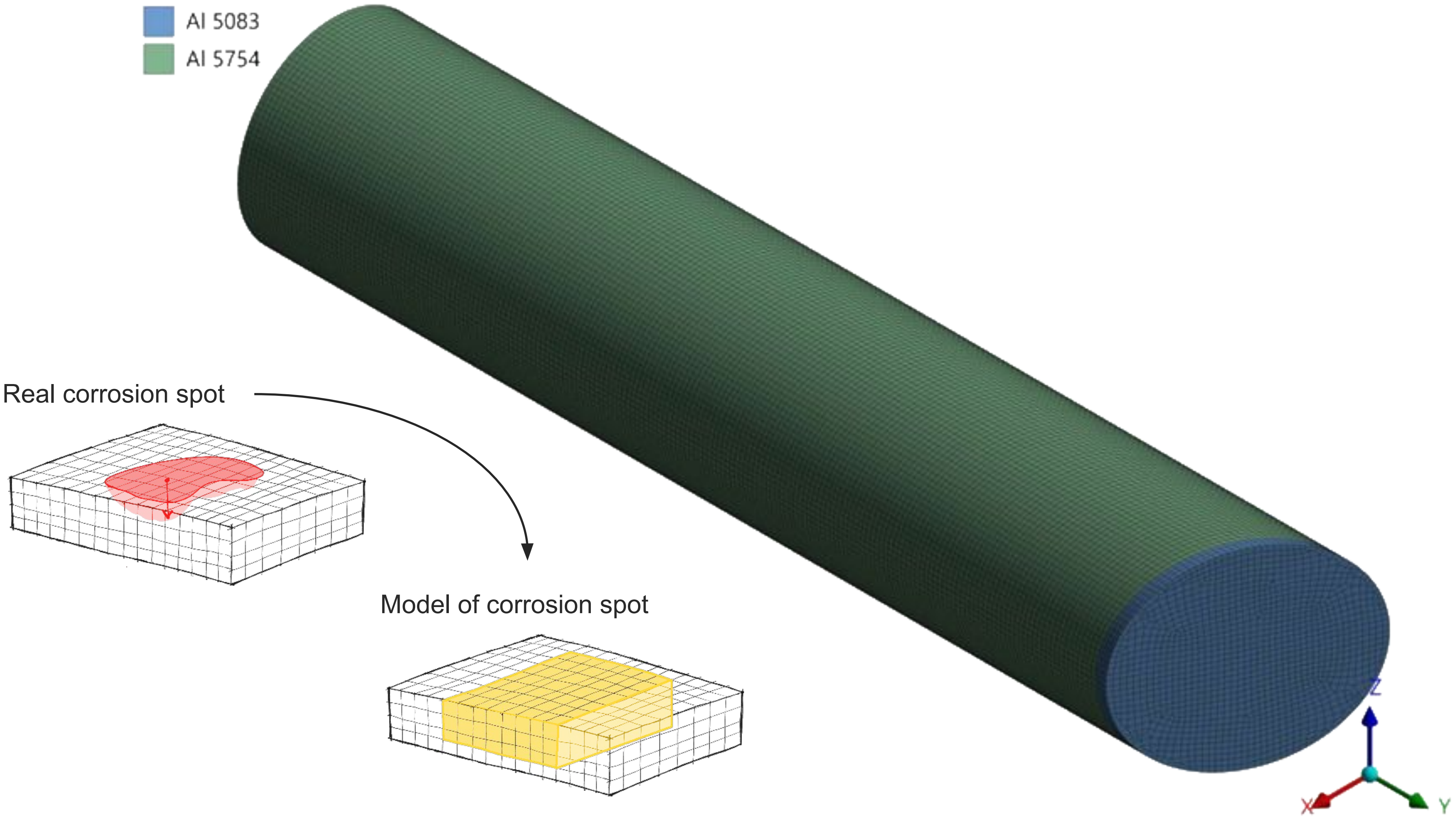
2024 Visual inspection position 265°

2024 BCD View Isotropic Scale

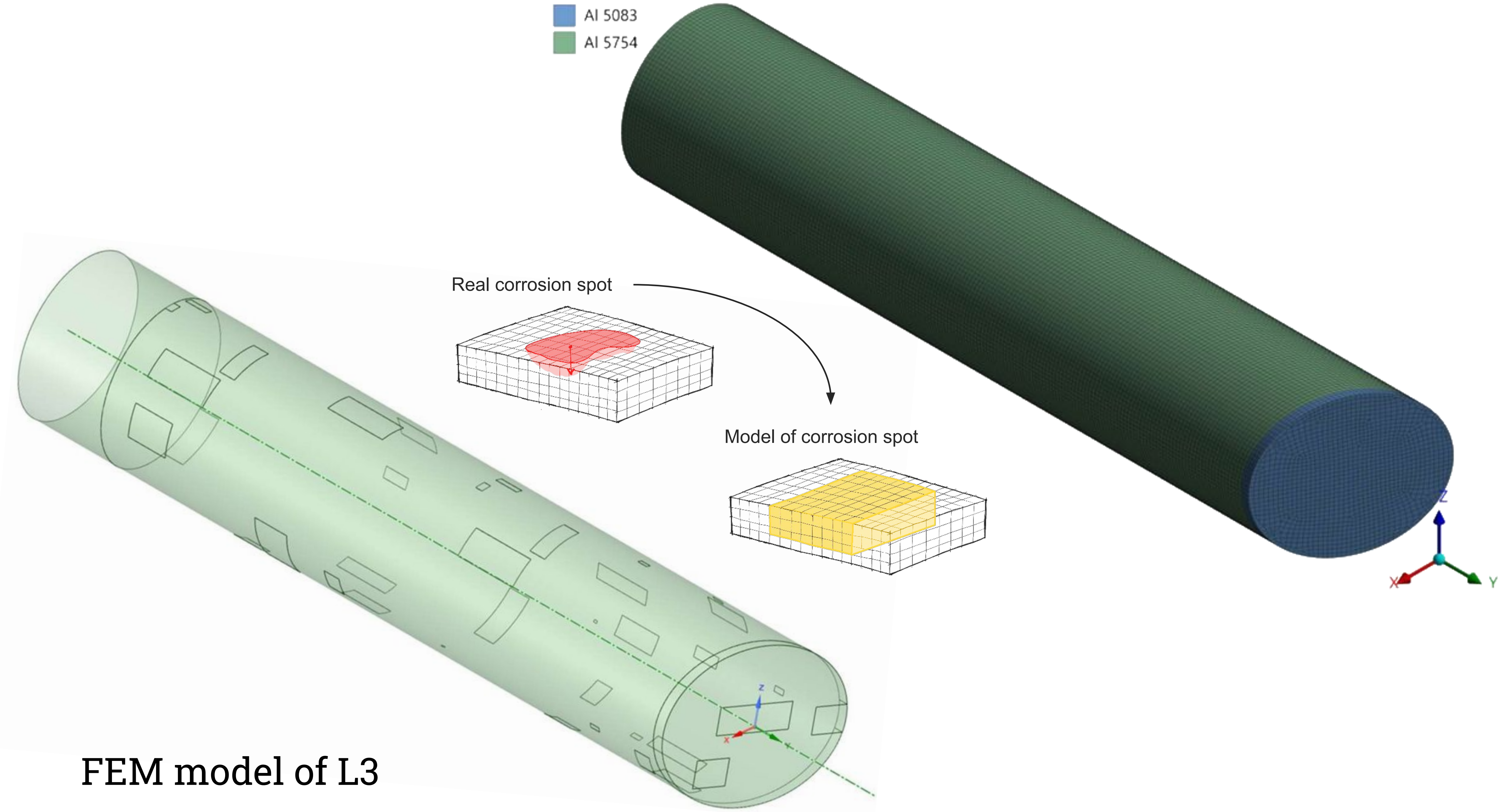




FEM model of L3



FEM model of L3



FEM model of L3

Connecting nuclear

What's the importance of *connecting* in ageing management?

For proper ageing management, to know your assets and become familiar with them, is important.

Practical *direct* experience is essential.

By learning from colleagues in the field, the chain of transferring direct experience is continuous.

Whenever I am going to perform something practical, I always ask colleagues to join me.

Either it's my colleagues helping me or it's me offering them an opportunity for obtaining direct experience.

Connecting nuclear

For innovation, what’s the importance of connecting?

Innovation is about the actual *realization* of something new.

Connecting theory to practice is important in the realization phase.

Often it also requires the help of colleagues, or external experts.

Involving others to collaborate to achieve your goals.


When was the last time *you* connected theory to practice?

Thank you for listening

Questions?

Extra slides

Preventing corrosion

Water quality management:

- 4,5 < pH < 7,5
  Typical: 5,5 – 6
- Conductivity < 300 µS/m
  Typical: 30 – 40 µS/m
- Chlorine levels < 5 g/m³ ≈ 5 ppm
  Typical: < 1 ppm

Limitations for in-pool use of materials:

- Chlorine-containing
- Copper, mercury, silver

Preventing corrosion

Water quality management:

3.5.1. Water chemistry

Maintaining high quality water in the fuel storage pool is the single most important factor in controlling corrosion of aluminium clad spent fuel assemblies and other aluminium alloy components stored in the pool. Treatment and purification of the water in the pool and any make-up water with the aid of filters and ion exchange resins is essential to achieve optimum storage performance. The recommended water parameters to minimize pitting and other forms of corrosion on aluminium clad spent fuel during extended interim wet storage are as follows:

Conductivity. The conductivity of the water in the fuel storage basin should be maintained as low as achievable and in the range 1–3 µS/cm for optimum corrosion protection. This level may be difficult to achieve in unlined pools. Conductivity in the range 3–10 µS/cm may yield satisfactory results provided the concentration of impurities such as chloride ions is low. There is some evidence that pitting may be suppressed below 50 µS/cm, depending on other parameters. Values near 200 µS/cm are known to be aggressive for aluminium and lead to pitting.

pH. The pH should be maintained in the range 5.5–6.5 in reactor pools. This pH level will minimize uniform corrosion. Pitting corrosion is not affected by pH in this range. Tight control of pH is essential in reactors where the same cooling water is shared by the core and the fuel storage basin. In away-from-reactor storage pools, a wider range of pH, 5.0–8.0, may be permissible. Irradiation is known to reduce the range within which the protective aluminium oxide is stable and can result in increased turbidity from precipitation of aluminium hydroxide from the water.

Chloride (Cl). The chloride ion content of the water should be maintained as low as achievable and at less than 1 ppm for optimum corrosion protection. This level is generally achievable if water conductivity is maintained in the 1–3 µS/cm range. Chloride ions break down the passive film on aluminium and promote metal dissolution.

Sulphates (SO_4). The total sulphate ion content of the water should be maintained at less than 1 ppm for optimum corrosion protection. However, for unlined pools where water quality is difficult to control, sulphates at or below 10 ppm should give satisfactory protection. An increase in sulphate concentration results in a decrease in thickness of the protective oxide film, with a corresponding increase in susceptibility to pitting corrosion.

Heavy metals. The concentration of copper, mercury, silver and other heavy metal ions should be maintained at or below 0.02 ppm. Heavy metal ions are extremely aggressive in causing pitting corrosion of aluminium, as they deposit readily, forming strong galvanic cells. These ions have strong synergistic reactions with chloride, bicarbonate and calcium ions. Reduced metals in the basin sludge or particles in the basin water can deposit and form galvanic cells, leading to localized corrosion of aluminium cladding.

Other impurities. Impurity ions such as iron, aluminium, nitrates and nitrites should be maintained at levels as low as possible. Normal deionization of the water in the storage pool to conductivity levels of 1–3 µS/cm should keep these impurities at or below the 1 ppm level. The presence of impurity ions increases water conductivity and the flow of corrosion current, thereby increasing the corrosion of the aluminium cladding.

Hardness. The carbonate hardness of the water should be maintained at 60 ppm or less when possible. Carbonate and bicarbonate ions can react synergistically with chloride and copper ions, resulting in increased pitting of aluminium. Soft water, defined by a carbonate content of 60 ppm or less, is not as aggressive in causing aluminium corrosion as hard water. Continuous deionization of the basin water softens the water, as it removes calcium carbonate and other ions contributing to the hardness.

Temperature. The water temperature should be maintained at 40°C or below. The rate of pitting at 40°C has been found to be five times that at 25°C. The density and probability of pitting have been found to increase with temperature. The corrosion rate of uranium metal increases dramatically with increasing temperature.

Radiation effects. Gamma radiation from irradiated fuel assemblies, ^{60}Co or radioactive caesium sources can have some effect on materials stored in fuel storage pools. Gamma fluxes have little effect on the properties of the cladding, and the radiation field does not promote any significant increase in corrosion of the metals in wet storage. Gamma fields can degrade components subject to radiolytic decomposition, such as neutron absorbers that contain organic materials and rack configurations that trap water. In the latter case, radiolytic decomposition can result in gas formation and a consequent buildup in pressure.

Replacing beam tubes

Beam tubes R1 and R2 have been replaced as part of the installation of the cold neutron source.

Due to significant amounts of radiation, distance is required to limit radiation doses. This adds up to the complexity of the task.

What about inaccessible beam tubes ?

Lack of data results in the need to use statistics for probabilistic extrapolation. This leads to uncertainty and to accept this a certain confidence interval is chosen.

Extrapolation and evaluation of *corrosion surface area* and *number of spots* is done by using the Erlang distribution.

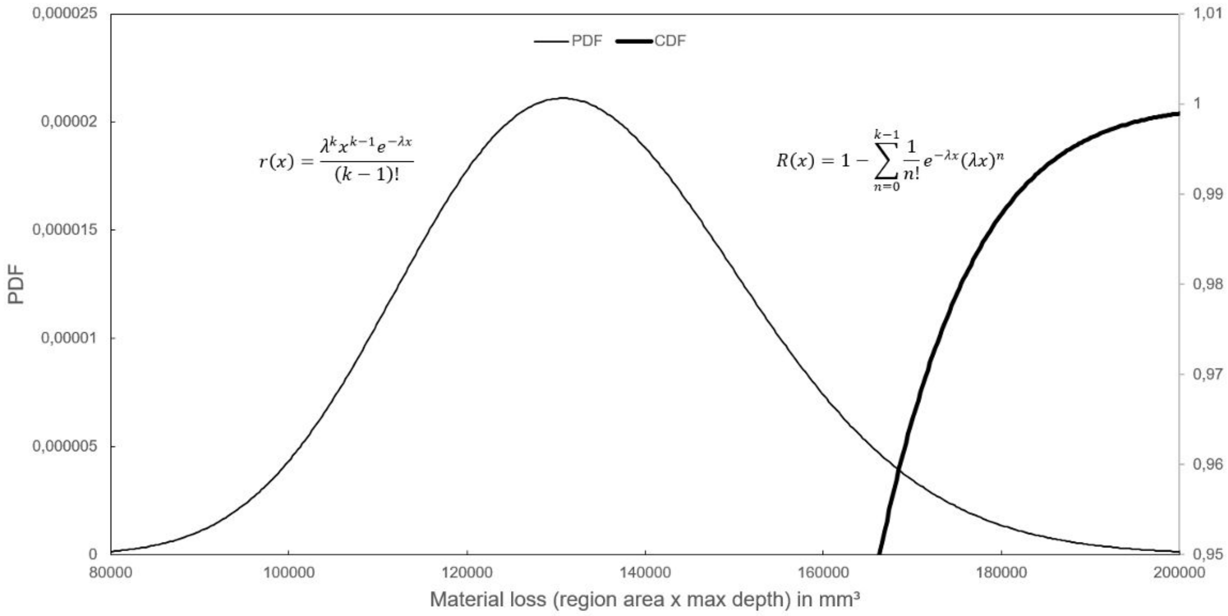


Figure 35: Erlang distribution for k = 49 and $\lambda = \lambda_{2\sigma}$ = 0,00037. At the intersection of the CDF with the x-axis (y = 0,95) the 95% probability limit value is found.

Acceptance criteria

The acceptance criteria for strength, ASME III:

- tensile = membrane (Pm)
- combined = tensile (Pm) + bending (Pb)

'Acceptance criteria' for stiffness:

- increasing load until buckling instability
- safety factor based on critical buckling load

5 Acceptance criteria

The acceptance criterion is from ASME III subsection NB, article 3210 [12] and from ASME III subsection A article XIII-3141 [13]. The membrane (P_m) and bending component (P_b) of the stress intensity field must fulfill the following criteria:

$$P_m < S_m$$
$$P_m + P_b < 1.5\, S_m$$

The material data for the Al alloys provided will be used to determine the maximum allowable stress intensity (S_m) from the Yield strength (S_y) according to Section II, Part D, Mandatory Appendix 2 for welded pipes.

$$S_m = \frac{2}{3}\, 0.85\, S_y$$

Buckling of the pipe

Being a shell under external load the component can be subjected to the instability of compression. This is evaluated with the buckling analysis for the first 4 buckling modes. This consists in a static structural analysis with the application of a gradually increasing load to seek the load level at which the structure becomes unstable. The outputs from the buckling analyses are the safety factors from the critical buckling load for each case.