Planning and managing an international testing programme:
THE INCEFA SCALE EXPERIENCE

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Overview of the talk

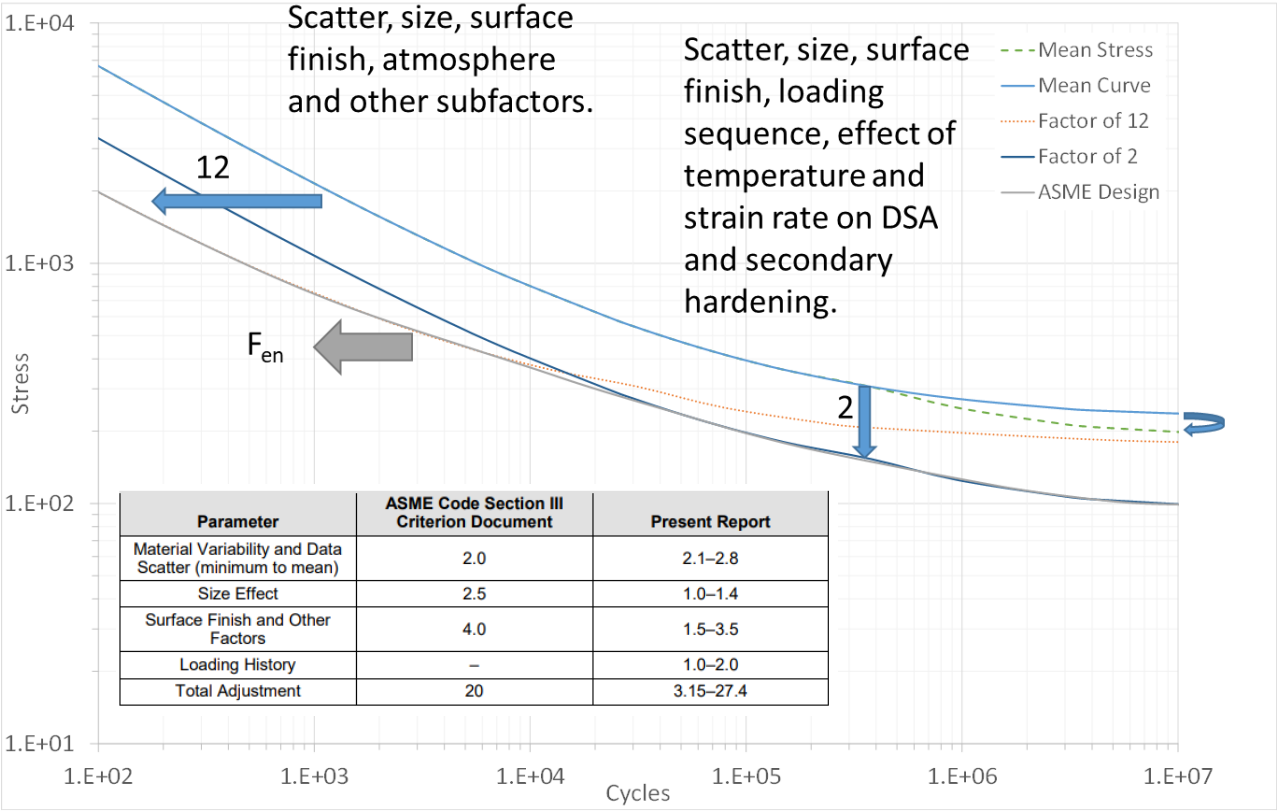
- INCEFA-SCALE is a c ~£7m EU funded environmental fatigue project.
- It follows on from INCEFA+, with the previous successes introduced by Kevin in the previous talk.
- It involves 20 organisations from 11 different countries on 3 continents.
- Testing is planned over 3 x 1year phases.
- How do we define and carry this out?
- Where’s it up to?

First things first, what are we going to do?

- Following INCEFA+, we needed to find out what EAF assessment gaps the industry would benefit from researching.
- The beginning of the project consisted of asking these questions:
- What are the high value research targets for the industry to make progress?
- What's missing from the literature and dataset defining environmental fatigue assessment procedures?
- What hypotheses can we test to achieve our aim?

We obtained industrial context

- Table 5-2 in NUREG CR/6909 Rev 1 demonstrates factors on life to air design curve.
- Most supported by test data (including INCEFA+).
- More understanding is required as to how onerous each variable is on fatigue life.
- Also there is an apparent lack of data justifying loading history effects.
- More data necessary to challenge factor of 2.



Parameter	ASME Code Section III Criterion Document	Present Report
Material Variability and Data Scatter (minimum to mean)	2.0	2.1–2.8
Size Effect	2.5	1.0–1.4
Surface Finish and Other Factors	4.0	1.5–3.5
Loading History	–	1.0–2.0
Total Adjustment	20	3.15–27.4

Why we are Doing What we are Doing: Design Curve

The factors on life are needed to account for variations in fatigue lives in the low-cycle regime. Based on the previous discussions, the effects of various material, loading, and environmental parameters on fatigue lives may be summarized as follows:

- The results presented in Table 5-1 were used to determine the factors that were applied to the mean value of fatigue life to ensure that the resultant value of fatigue life bounded the 95th percentile of the materials and loading conditions of interest.
- For rough surfaces, specimen size does not significantly influence fatigue lives. However, specimen size does, in some cases, significantly affect fatigue lives for smooth specimens. Absent additional test data that indicate otherwise, factors ranging from 1.0 to 1.4 on fatigue lives were used in the reanalysis of the larger fatigue database to incorporate size effects on fatigue lives.
- Factors ranging from 1.5 to 3.5 were used to incorporate the effects of surface finish on fatigue lives in air. Because additional data are not available to verify that the surface finish effects are lower or insignificant in LWR environments, this investigation used a range of 1.5 to 3.5 to account for the effects of surface finish on the fatigue lives of carbon and low-alloy steels and wrought and cast austenitic SSs both in air and LWR environments.
- Because variable loading histories primarily influence fatigue lives at low strain levels (i.e., in the high-cycle regime), the mean air fatigue ε–N curves were adjusted by a factor of 2.0 on strain to account for damaging cycles that occur below the constant-strain fatigue limit of the material. Factors ranging from 1.0 to 2.0 were used to incorporate the possible effects of load histories on fatigue lives in the low-cycle regime.

Need the IFD to tackle this.
Also trying new methods for determining the factors on stress/strain and life require the IFD

$F_{\text{en-Threshold, incorporated, integer}}$
ASME code case in an advanced state.
Nearly ready to realise a benefit here!

Tackling this aspect is needed for further progress.
To do that we need to explore models and understand behaviour.
Basic fundamental research that can then be used to build fully justified methods from.

Why we are Doing What we are Doing: F_{en}

- That's the design curve, what about Fen and its weaknesses in NUREG/CR-6909 Rev 1?
  - Low predictions for complex strain loading cycles: unknown reason.
  - Limited data on temperature transients and spectrum loading: recommended to test complex loading effects.
  - Rotation of the mean curve and its implications for Fen.
  - Data underpinning the threshold.

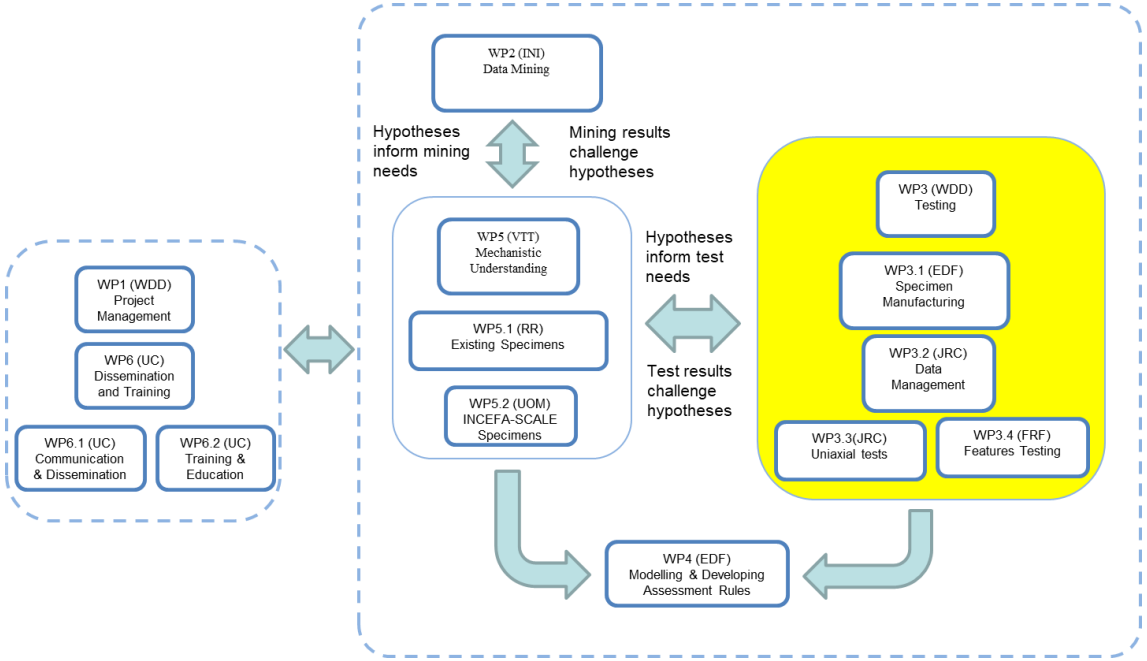
SNW, spectrum loading, TMF loading, Thermal-shocking.
Multiple organisations across the globe.
ASME code case in an advanced state. Nearly ready to realise a benefit here!

EPRI Component testing for the win!

Small potential benefits, but INCEFA-SCALE data can help unlock them.

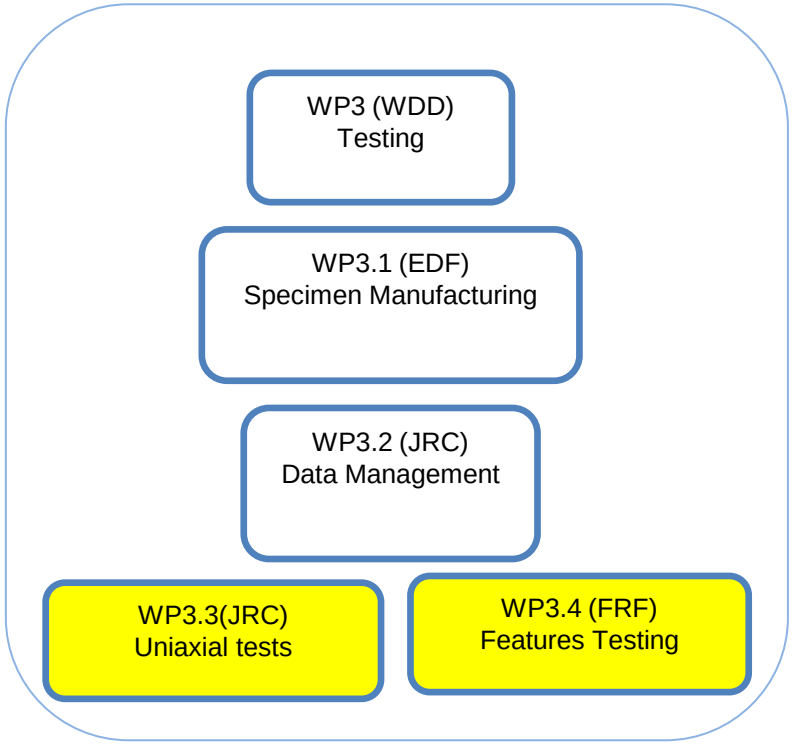
The project was structured

- Key issue: discrepancy between failure OPEX and predictions.
- Transferability of laboratory test data (i.e. design curves) to component scale a key issue.
- Complementary Work Packages (WPs) were defined to maximise value.
- All WPs aimed at meeting hypotheses to challenge or validate N6909 factors.
- This talk mainly presents the testing aspects (WP3).



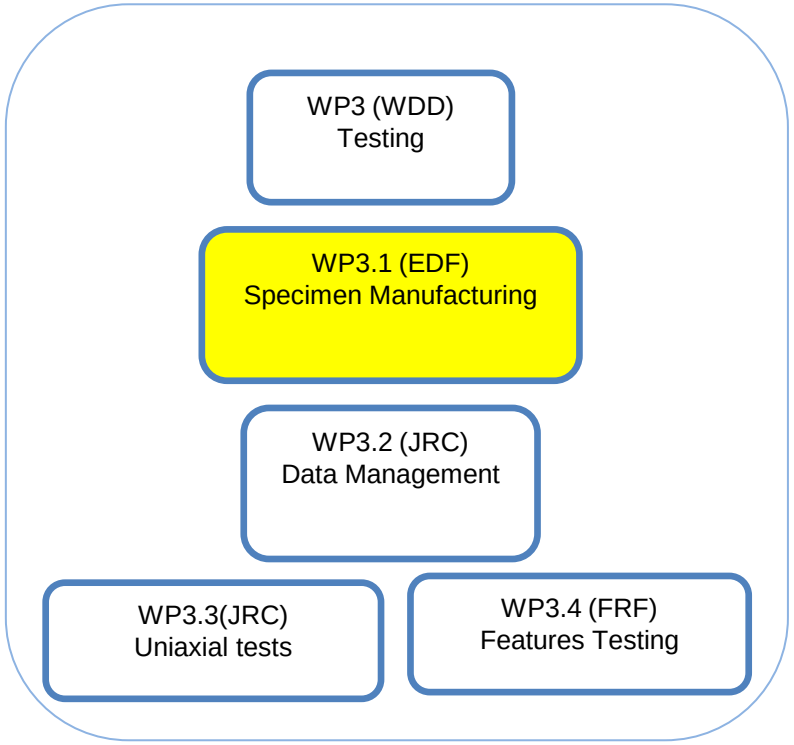
Who’s doing what for the testing?

- Actual testing split into 2 areas, looking at loading/surface finish/environment (uniaxial, WP3.3); and geometry (features testing, WP3.4).
- Lab commitments from the consortium obtained to define test numbers.



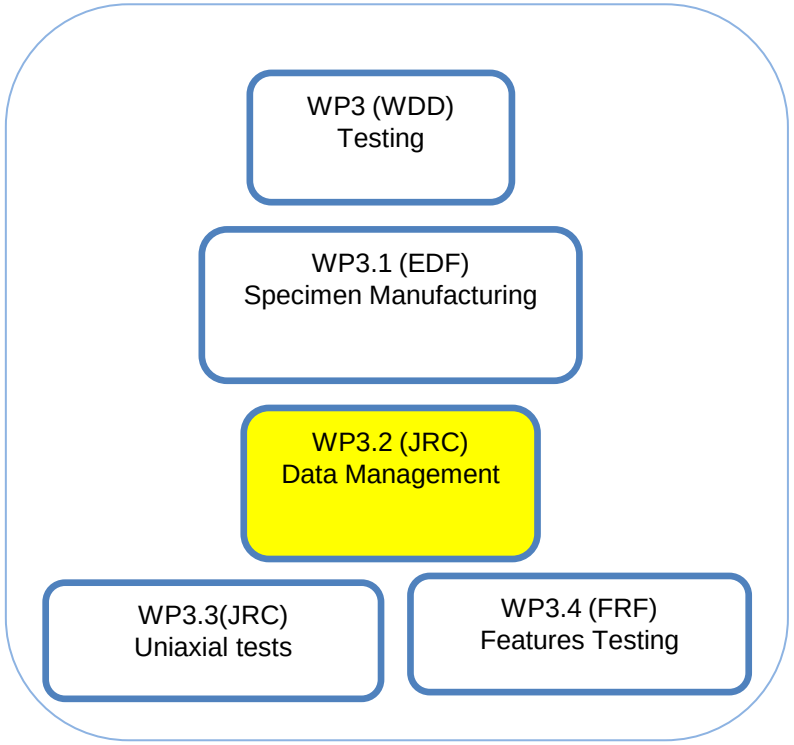
We'll need specimens…

- Single source of (~90/year) specimens used to maintain consistency in tooling and machining parameters.
- This ensured a consistent finish across the specimens.
- Features testing required notched specimens.
- This involved detailed characterisation (WP5) to ensure a finish consistent with uniaxial specimens.



…and somewhere to put the data

- MatDB used as data repository for all INCEFA data.
- Enables consistent formatting and reporting of data.
- Data rated as it comes in by Expert Panel.



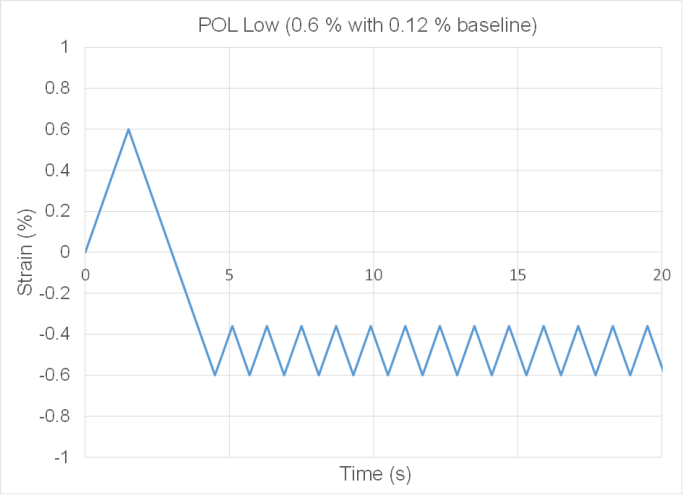
Next, we define the hypotheses under initial consideration

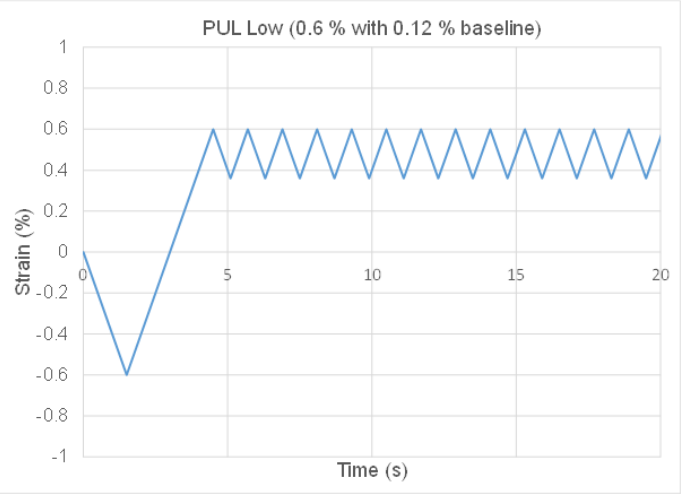
The Modified Goodman Mean Stress correction is already providing significant cover for the effect of transitional mean stresses from Variable Amplitude (VA) loading, and thus the VA transference factor of 1 to 2 in 6909 is at least partially double accounting.

- One example of a working hypothesis is shown here.
- Several were initially defined to kick the testing off.
- Lets work through how we go about addressing this example.

Turn the hypothesis into a test

- Waveforms designed to include mean stress, by adding in a mean strain, easy.
- Identical strain amplitudes included, with significant compressive and tensile mean strains.





Success!

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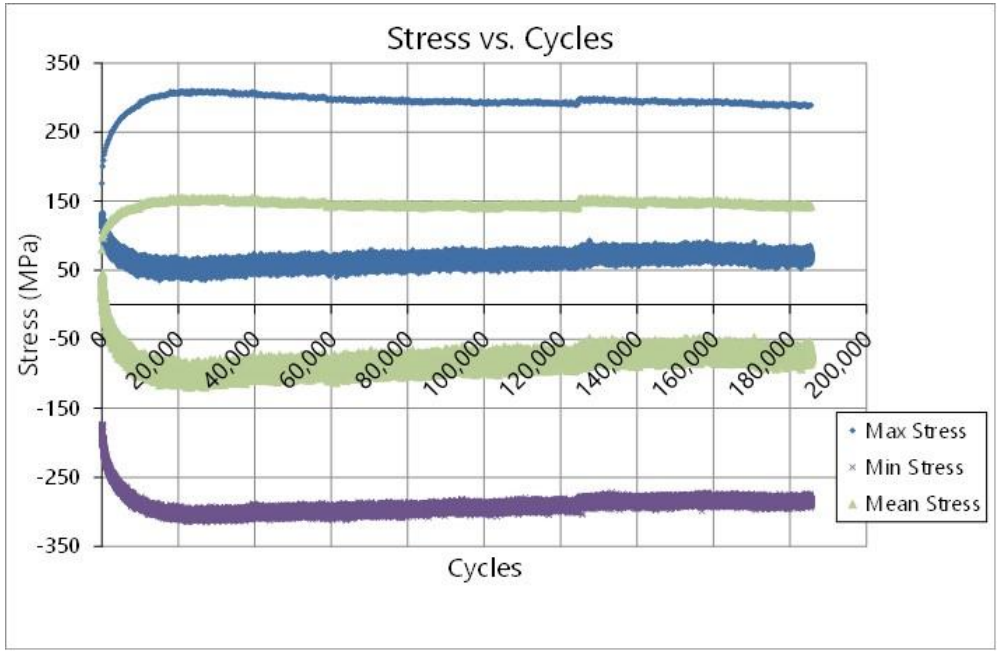
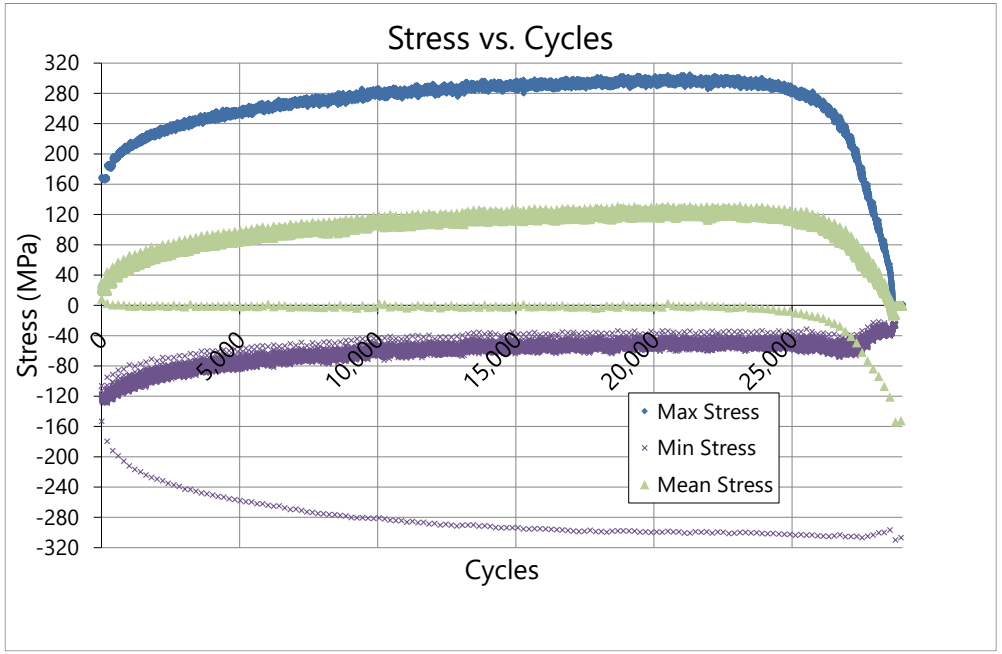


PUL

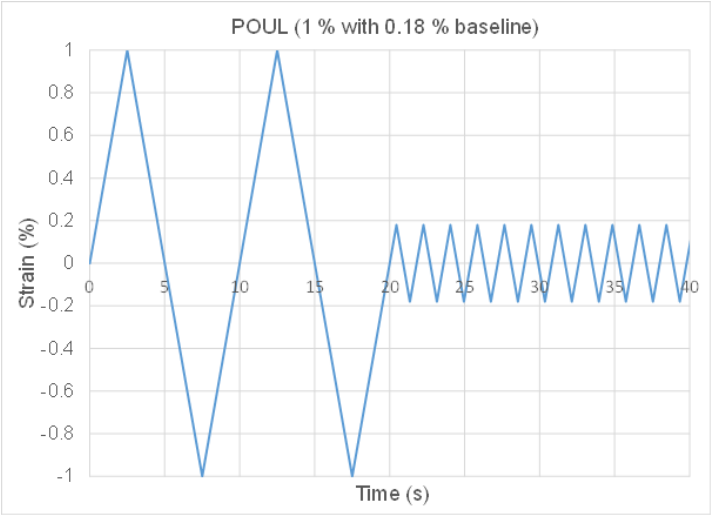


- Significant mean stresses developed in both cases.
- Significantly longer lives were observed with compressive mean stress.

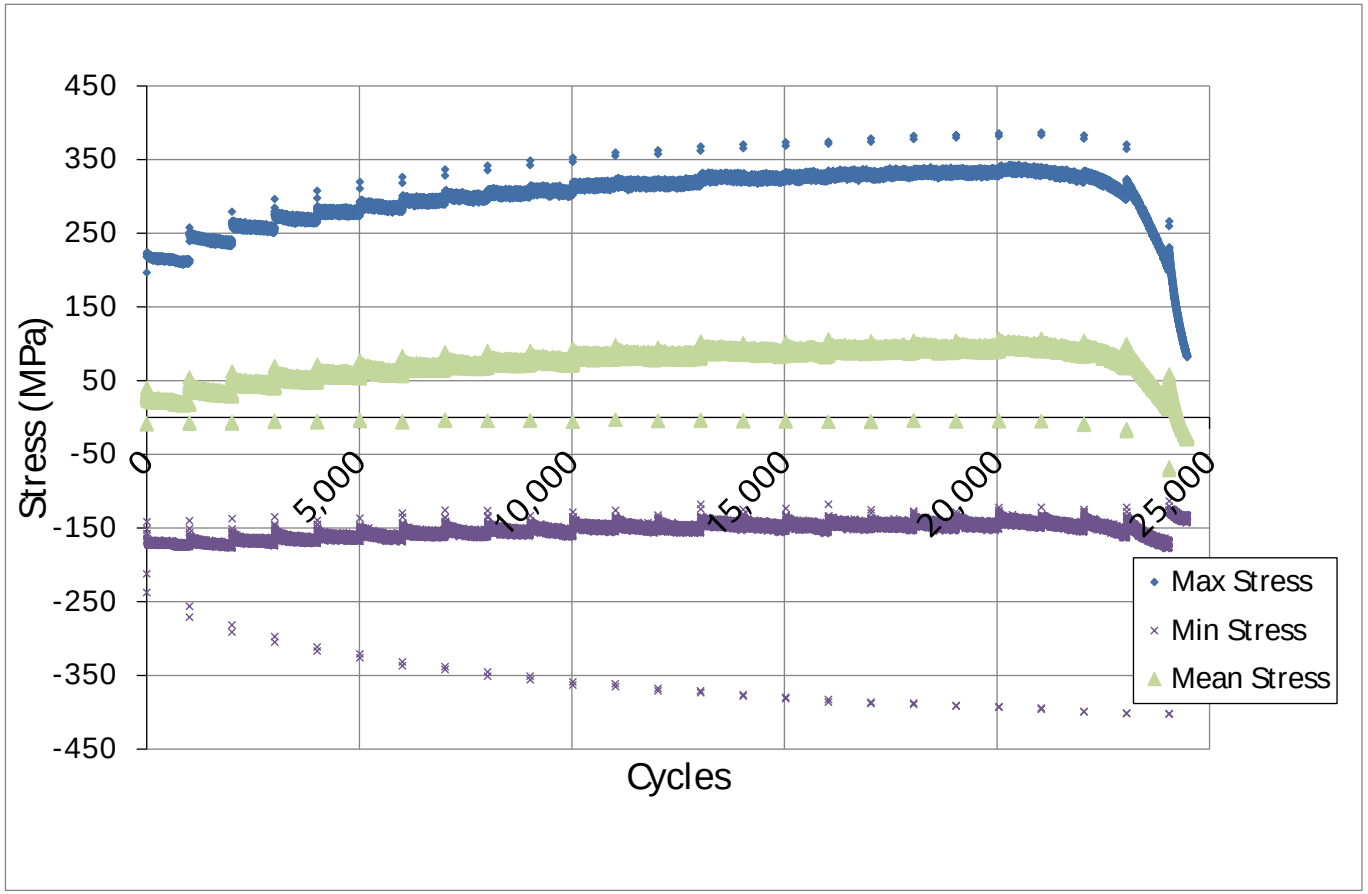
Let’s add another couple of hypotheses!

- In PWR environments, the effects of hardening on fatigue life should not be treated as additional to effects of environment.
- In PWR environments, negative effects from hardening, environment and surface roughness are not multiplicative.

- Waveforms designed to introduce significant hardening.
- Different surface finishes incorporated into test regime.
- PWR and Air environments tested to assess environmental effects.



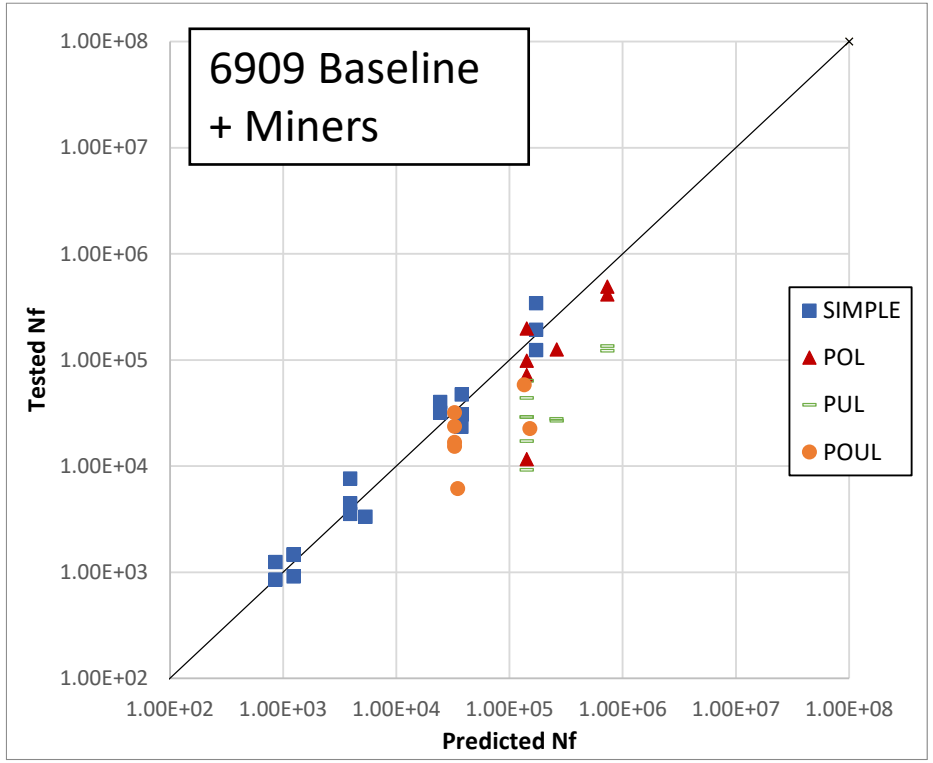
We got hardening, but also mean stress

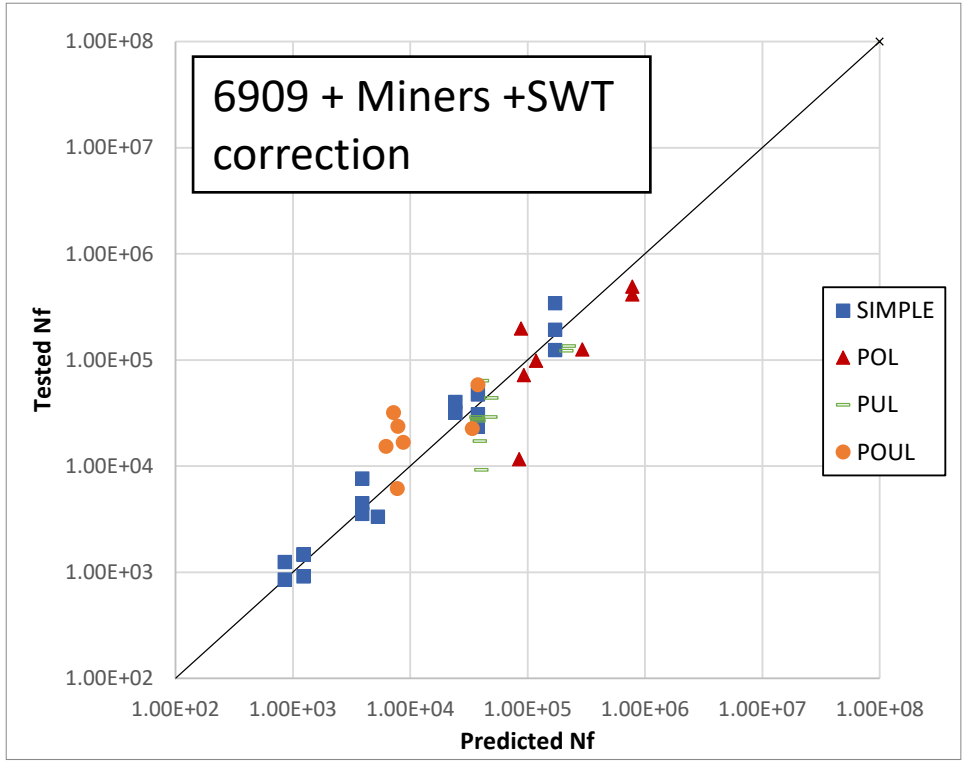


- Life comparable with PUL, but different strain amplitudes in tests.
- A persistent mean stress was induced so it is more challenging to isolate the effects of hardening.

Lets get a decent mean stress prediction

- Plots show performance test data against N6909 curve for baseline cycles with Fen included for PWR tests.
- SWT approach offers a good mean stress correction.

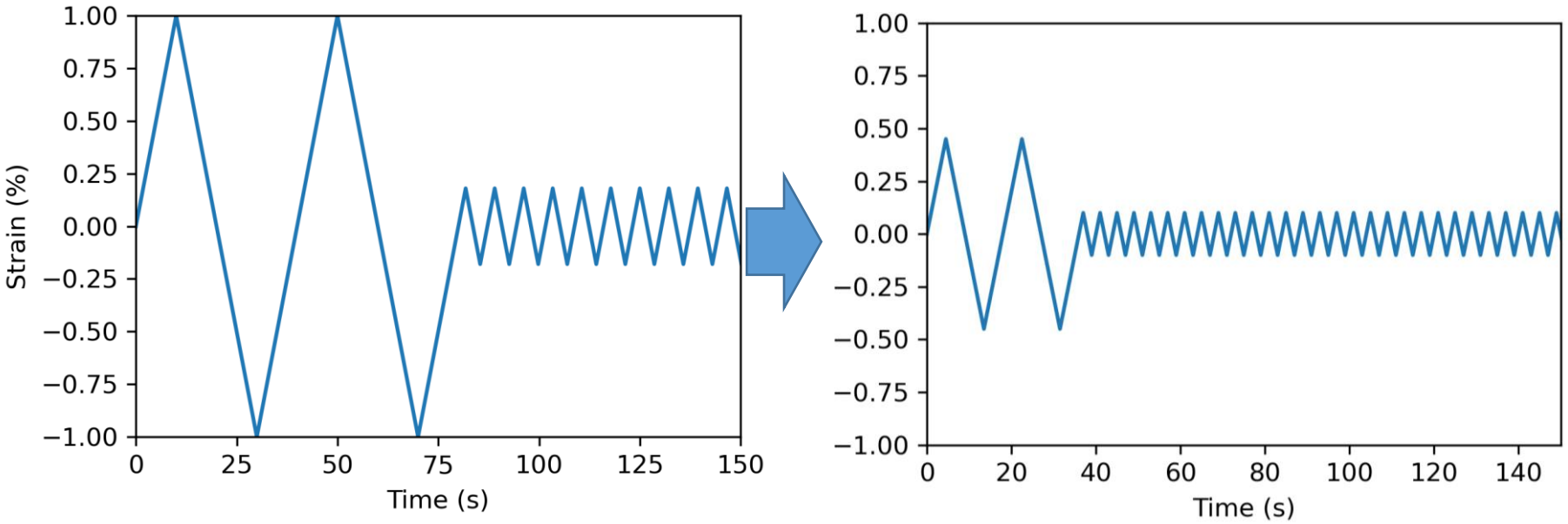




What else did the Phase 1 data show?

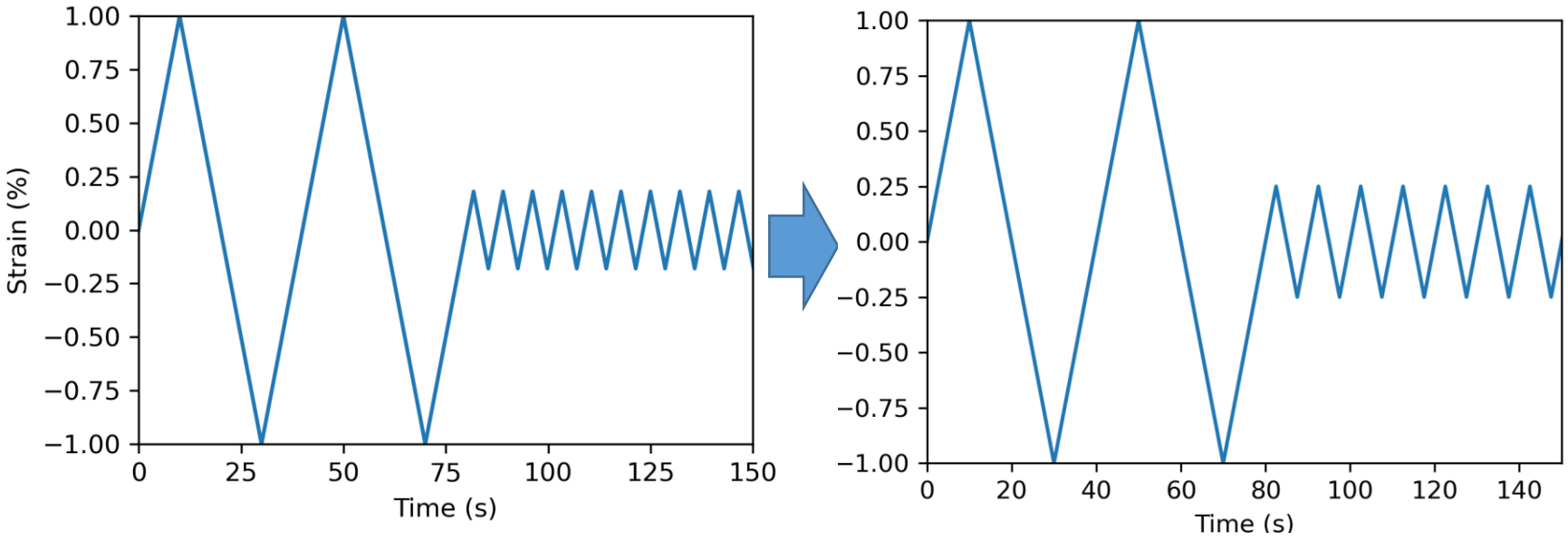
- Examination of the available data shows that the environmental effect may be lower or turn off in some cases.
- So lets throw in some tests to examine this (reduce the strain amplitudes).
- New hypothesis for Phase 2!

Fen threshold appears to be increased by prior hardening at higher strain amplitude, It is hypothesised that for Fen to take effect a certain plastic strain amplitude is required.



What else did the Phase 1 data show?

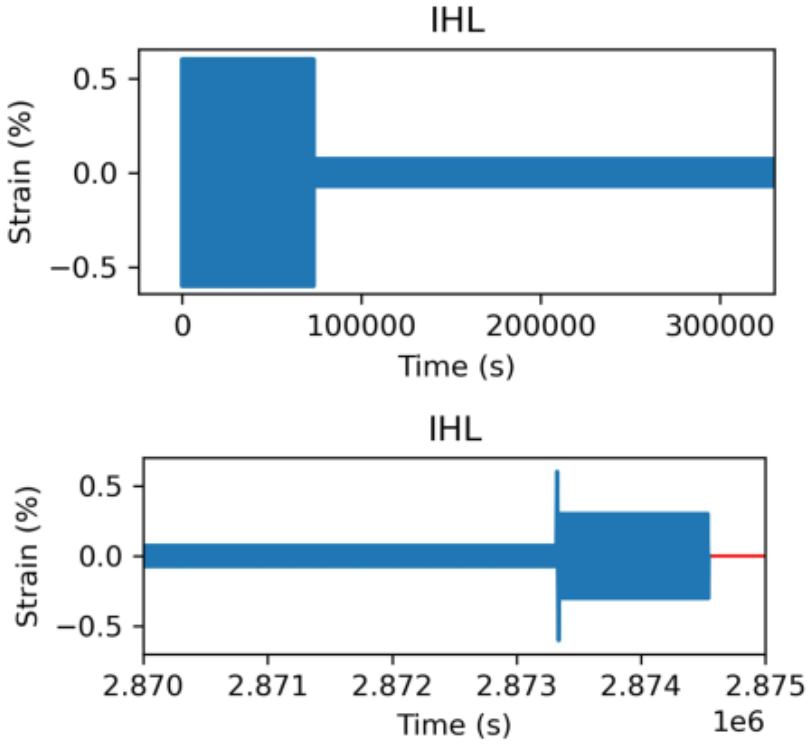
- Also can we remove the mean stress from the POUL to assess hardening alone?
- Again lets throw another test at it and get some data (increase the baselines).
- Re-addresses the Phase 1 hypotheses, and the new Phase 2 hypothesis.



Better have another hypothesis!

Design guidance methods provide suitable protection against sub-endurance limit short crack growth under VA loading.

- Waveform designed to initiate cracks using R5 approach (assumed 350µm crack).
- Includes 1,000,000 cycles at 0.07% strain amplitude.
- Supports factor of 1.6 as opposed to 2 on stress, would address questions of sub-endurance growth.



OK, so now we've defined and got data from Phase 1, and have defined new Phase 2 tests

- We need to look at the data and see how our predictions looked against the data we have.
- Also some of these Phase 2 tests look pretty time-consuming..
- We'd better get accurate predictions based on improved hardening predictions from the stresses we've seen.
- Also we've now got a good grip on the mean stress effects.
- Lovely, new predictions for Phase 2.

Now the real challenge begins…

- We have some confidence in our predictions, and solid working hypotheses.
- However, due to unavoidable delays we still have Phase 1 data outstanding.
- We can’t sign off any conclusions on those hypotheses until that’s in.
- We also ideally need the Phase 1 and 2 data to define Phase 3.
- But we won’t get it all on time.

Let’s define Phase 3 anyway

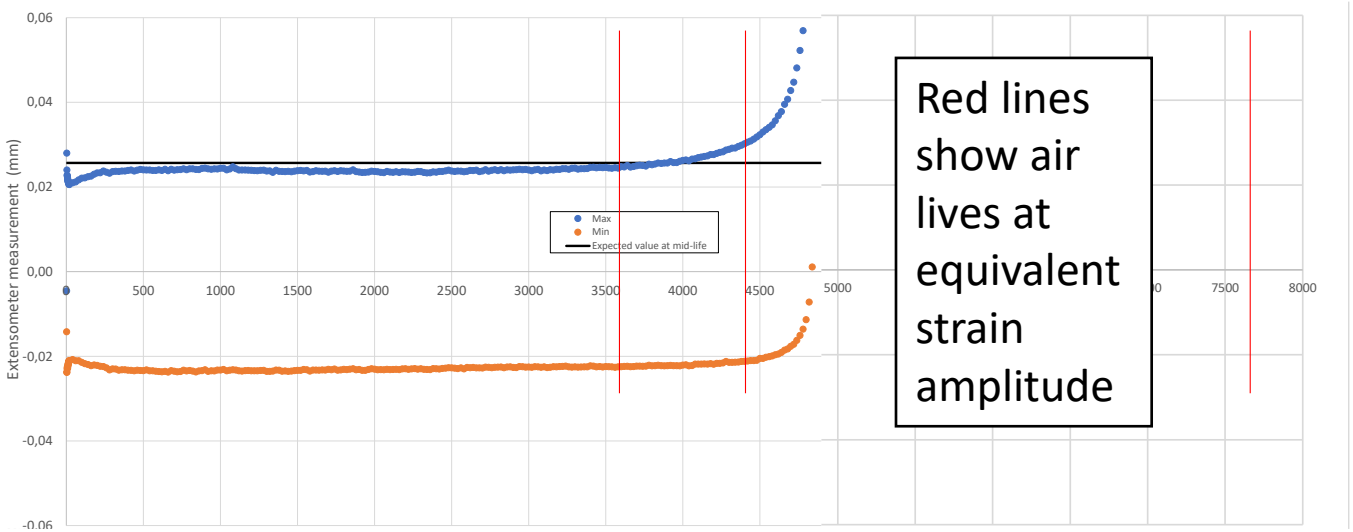
- All of the development we’re looking at with our models eventually lead to predicting life for plant realistic loading scenarios.
- Therefore we need to get closer to these in the tests.
- Spectrum loading (i.e. multiple strain amplitudes in one test) will be considered.
- We’ll also address any gaps from the previous tests.

Meanwhile, features testing has its own hypotheses

Notch effects on fatigue behaviour of stainless steels in LWR environments are adequately accounted for in assessment procedures.

- Multi lab and specimen design programme designed (2 notch depths).

- Targeting von-Mises strain amplitudes at notch tip for comparison against uniaxial data.
- Initial diagnostic tests underway to validate FEA stain amplitude predictions.

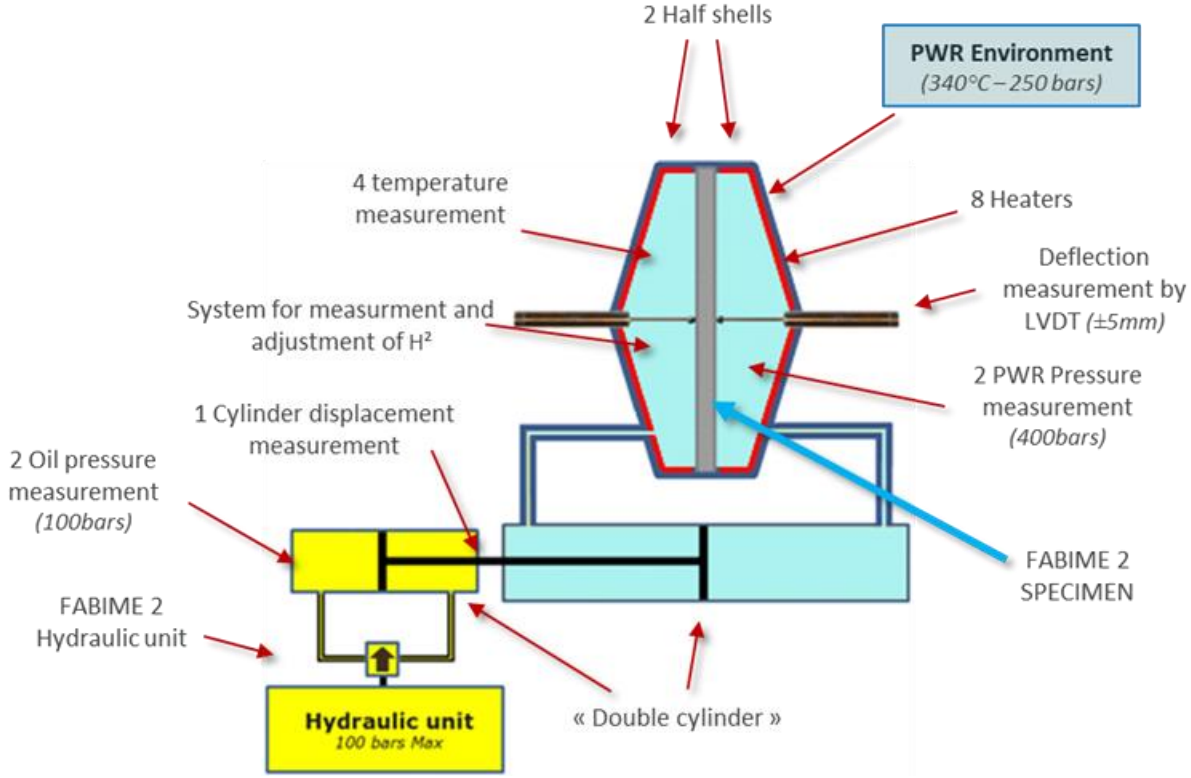


Red lines show air lives at equivalent strain amplitude

Another hypothesis under consideration

The effects of VA loading on in-phase equi-biaxial loading are not significantly different to those under uniaxial loading.

- Fabime2 diaphragm specimens to be tested under VA loading at CEA.
- Aim is to initially test under constant amplitude to ensure parity, then investigate VA POUL loading.



What will/are the test data and specimens being used for

- Comparison with codified life predictions.
- Development of best estimate life predictions.
- Advanced hardening models to predict stresses.
- Validation of damage parameters for multiaxial loading.
- Striation counting and advanced characterisation providing crack growth rates and initiation predictions.
- Data mining enabling assessment of effects of specific variables.
- All applicable to full scale component assessments.
- Validation planned against EPRI component test at end of project.

Thank you & thanks to INCEFA-SCALE participants!

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