Life Extension of Nuclear Plant Facilities through Monitoring and Detailed Analysis - 16175

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ABSTRACT

The UK has accumulated a substantial legacy of radioactive waste from various civil nuclear and defence programmes. Presently, however most of the UK radioactive waste is generated from nine power stations which generate approximately one sixth of the of the country’s electricity. Irradiated fuel is removed from these reactors and safe management of the radioactive solid and liquid effluents is required. The safe management of these effluents is essential.

Sellafield, in West Cumbria UK, contains two reprocessing plants, one designed to process nuclear fuel from Magnox reactors (CO_2 cooled with Uranium bar fuel) and the other to process nuclear fuel from Advanced Gas cooled Reactors and Pressurized Water Reactors. The reprocessing stage enables extraction of fissile material for recycling. This leaves a volume of dilute but high-level waste. The high-level radioactive liquid waste is concentrated to reduce its volume and then incorporated into borosilicate glass, using a process called vitrification. The glass is then poured into stainless steel containers and placed in long term storage.

This required concentration of HLW liquor is achieved using a suite of aging evaporators. All evaporators are of similar design constructed from corrosion resistant stainless steel having dimensions height ~11m, internal diameter 3.05m and capable of holding 13.7m^3 of liquor. The basic principle of operation is to heat the dilute liquor under partial vacuum, at constant volume, until the target concentration is achieved. Heating of the liquor is achieved using steam heated coils within the evaporator, and steam in the jacket which surrounds the lower half of the evaporator vessel. The evaporator is then brought to atmospheric pressure and the concentrated liquor is ejected whilst hot. The evaporator is then cooled with water cooled coils and a water filled jacket. New dilute liquor is then added for a new batch. The process is then repeated.

As the evaporators reach the end of their original design life accurate prediction of the current condition of nuclear plant facilities is essential to safely justify continued plant operation by ensuring structural integrity. This poses a significant challenge as many aging UK nuclear facilities were not inherently built with inspection in mind.

The potential life limiting components of the HA evaporators at Sellafield are the surfaces that contact the product liquor at elevated temperatures i.e. the steam heated surfaces of the coils within the evaporator vessel and the vessel base and wall surrounded by the steam jacket. Each heating component is critical to the operational life of the evaporator – the removal from service of a coil heating component significantly reduces the operational flexibility and remnant life of this plant.

Over the last decade a variety of cutting-edge expertise and methodologies have been utilised to accurately measure and then predict the current condition of the plant and also to predict its remnant life.

This paper provides an overview of the development of several techniques deployed, namely non-destructive testing/inspection, in-house software development and finite element modelling. These methods have been validated by lab-scale or full-scale experiments along with historical plant data. These techniques have been evolved and refined for over a decade, providing vital insights into the physical behaviour of this complex reprocessing system. This enables not only accurate assessment of the current condition of the plant equipment but also allows scientifically underpinned predictions to be made of how it will behave into the future. This is critical for Sellafield as this knowledge feeds into their safety case to the Office of Nuclear Regulation to justify continued operation.

It is concluded that this integrated approach provides a robust analysis tool which has driven change and optimisation of plant procedures ensuring continued safe operation whilst extending the life of the facility.

INTRODUCTION

Sellafield, in West Cubria UK, contains two reprocessing plants, one designed to process nuclear fuel from Magnox reactors (CO_2 cooled with Uranium bar fuel) and the other to process nuclear fuel from light water of Advanced Gas cooled Reators [1]. Irradiated fuel is removed from these reactors and safe management of radioactive solid and liquid effluents is required. Reprocessing liquors containing >99% of fission products removed (HA liquors) from irradiated fuel are concentrated in Highly Active Evaporators at Sellafield. These concentrated HA liquors (HA raffinate) which are self-heating are kept in an array of water cooled tanks (HASTs) before being incorporated into glass in the Waste Vitrification Plant (WVP) prior to long term storage. This process is schematically shown in Figure 1.

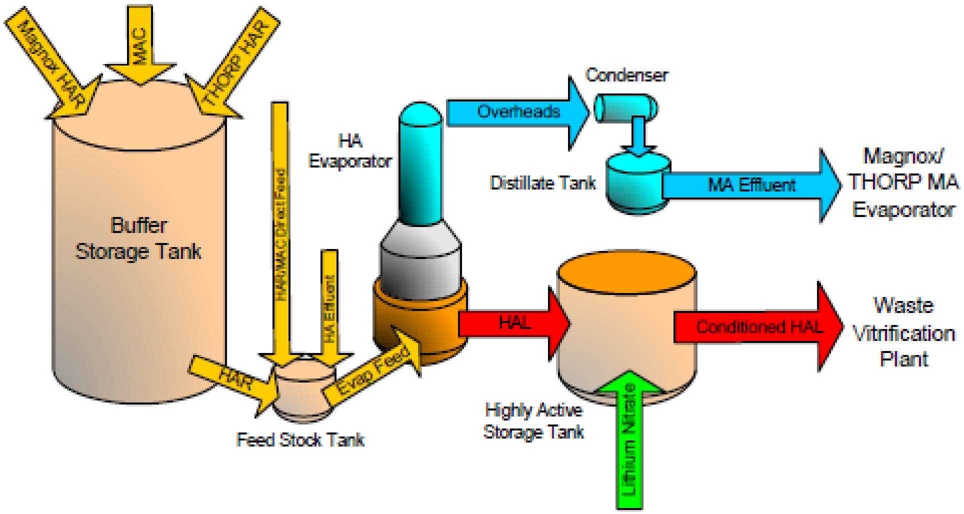

Figure 1: HA evaporator link with other processes [1]

The Highly Active Evaporators are vital to continue to process HA liquors and continue operations at Sellafield. This process is currently performed by a suite of aging evaporators pending the completion of a replacement evaporator. Sellafied Ltd therefore instigated a risk based longevity assessment of these HA facilities to provide confidence that continued nuclear fuel reprocessing will meet the current UK nuclear fleet energy needs until their final closure.

Evaporators

There are currently three HA Evaporators on the Sellafield site, denoted HA evaporators A, B and C. Evaporators A and B were built in the early 1960's and were designed to concentrate HA raffinate arising from the Magnox reprocessing plant. HA Evaporator C was built in the mid 1980's and can be used to concentrate HA liquors from both Magnox and Oxide reprocessing sites. All evaporators are of similar design constructed of corrosion-resistant stainless steel having dimensions height ~11m, internal diameter 3.05m and capable of holding 13.7m^3 of liquor, see Figure 2. The lower section contains a complex assembly of heating/cooling coils (4 coils in HA Evaporators A & B and 6 coils within HA Evaporator C).

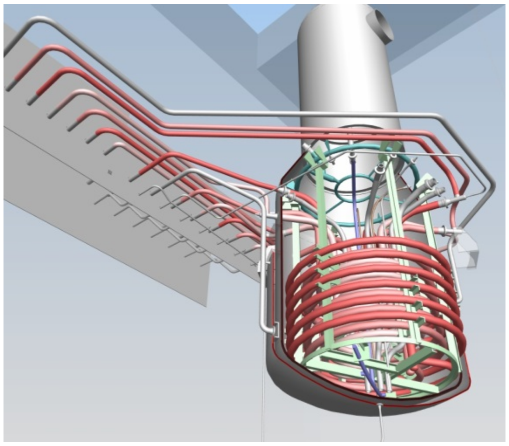

Figure 2: View of multiple stacks of cooling/ heating coils (in red) and coil supports (in green) in evaporator. Grey is for jacket pipes.

The basic principle of operation is to heat the dilute liquor under partial vacuum, at constant volume, until the target concentration is achieved. Heating of the liquor is achieved using steam heated coils within the evaporator, and steam in a jacket which surrounds the lower half of the evaporator vessel. The evaporator is then brought to atmospheric pressure and the concentrated liquor is ejected whilst hot. The evaporator is then cooled with water cooled coils and a water filled jacket. New dilute liquor is then added for a new batch. The process is then repeated.

Life limiting components

The potential life limiting components of the HA evaporators at Sellafield are the surfaces that contact the product liquor at elevated temperatures i.e. the steam heated surfaces of the coils within the evaporator vessel and the vessel base and wall surrounded by the steam jacket. This paper considers the steam heated coils only. Each heating component is essential to the operational life of the evaporator – the removal from service of one coil heating component significantly reduces the operational flexibility and remnant life of this plant. Although constructed from stainless steel continued operation has led to corrosion of the internal coils, which was accounted for in their initial design.

This paper provides an overview of a number of strands of plant examination, experimental and modelling work undertaken to fully appreciate all the factors contributing to metal temperature and hence corrosion rates in the High Active Evaporators at Sellafield and shows how these are combined within a Finite Element model to conservatively predict the remnant life and hence future throughput for Evaporator C.

INTRODUCTION TO FINITE ELEMENT MODELLING

ANSYS Mechanical software [2] was chosen to model the effect of future corrosion on stress and future life of the HA Evaporator C coils. ANSYS software is an internationally recognised comprehensive FE (Finite Element) analysis tool for structural thermal analysis, including linear, nonlinear and dynamic studies, provided by ANSYS Inc.

The huge advantage to using FE models is that it allows for increasingly more complex information to be incorporated into the model, which in turn allows for a more accurate representation of the Evaporator whilst in operation.

As more details have been incorporated into the FE model engineers and operators have improved their knowledge of the plant equipment and also increased their confidence in their understanding of its behaviour. This enables scientifically underpinned predictions to be made of how it will behave into the future.

This ability to accurately predict the behaviour of the HA Evaporator C subject to normal operational loads and extreme loads is essential in order to ensure safe operation, whilst maximising its full utilisation.

MODELLING PROCESS OF THE STEAM HEATED COILS IN EVAPORATOR C

A general overview of the input parameters incorporated into FE analyses of the steam heated coils is shown in Figure 3. This illustrates how the FE models incorporate numerous parameters based on actual on-line plant data, combined with statistical and numerical methods to predict the physical behaviour of coils during the processing of effluent waste.

These well-defined parameters are required to obtain conservative predictions from the FE modelling. This paper provides a brief overview of the primary input parameters and then discusses in greater detail the FE modelling approach.

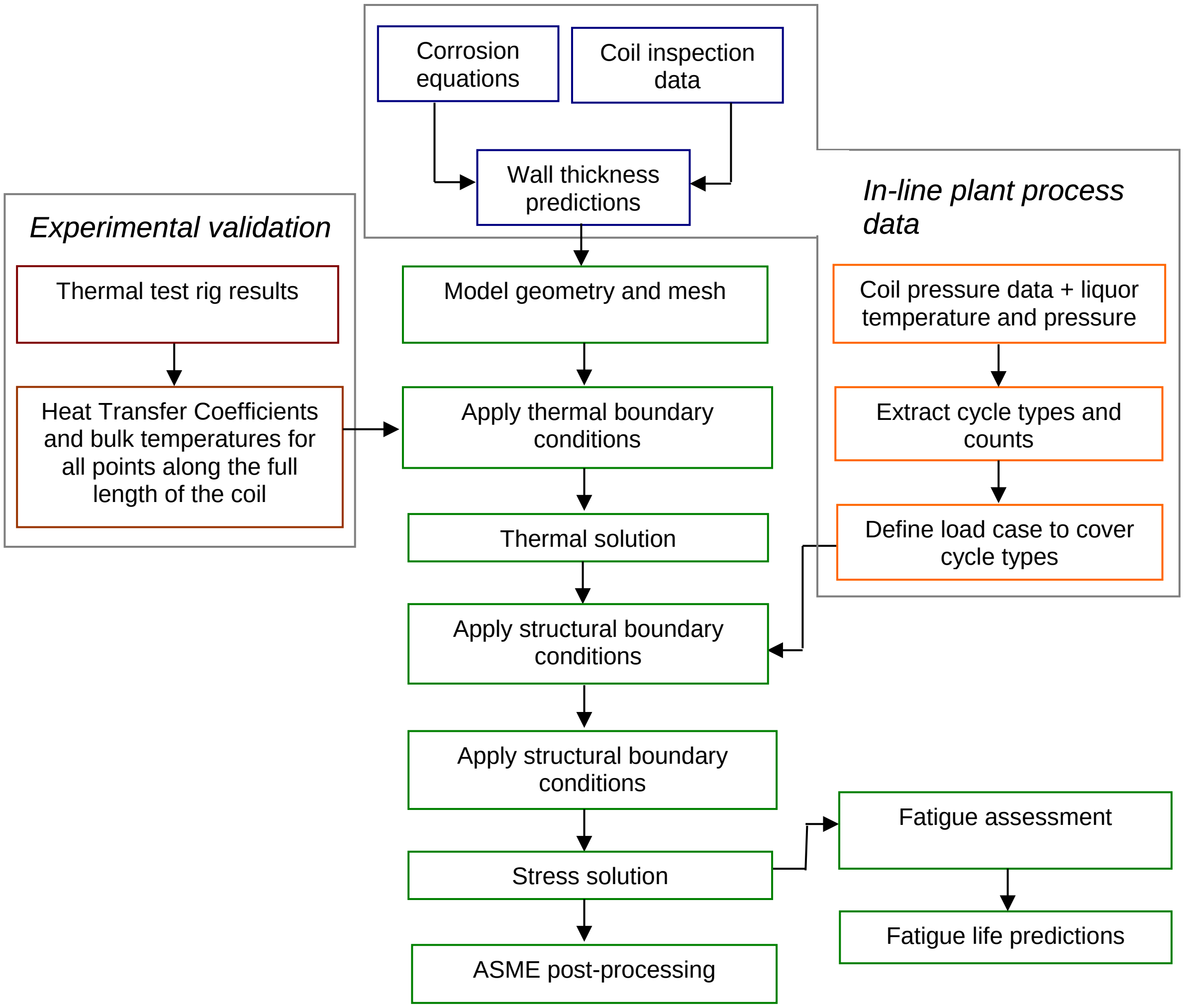

Figure 3: Outline of the modelling process of the steam heated coils in Evaporator C

Coil inspection data

Inspection of the coils posed a significant challenge as many aging UK nuclear facilities such as the HA Evaporator C were not inherently built with inspection in mind. These facilities are significantly radioactive and so are located in thick concrete cells making access extremely difficult.

Each heating component is essential to the operational life of the evaporator and so any inspection vehicle needed to demonstrate that it had minimal risk during retrieval. This level of confidence was achieved by the NNL manufacturing a full scale rig of all the coils at their facility in Workington, UK and fully testing the proposed system.

A ‘pig’ type inspection vehicle was developed which is capable of measuring the thickness of the steam heated coil components within the evaporator. This device utilises ultrasonic detectors as shown in Figure 4.

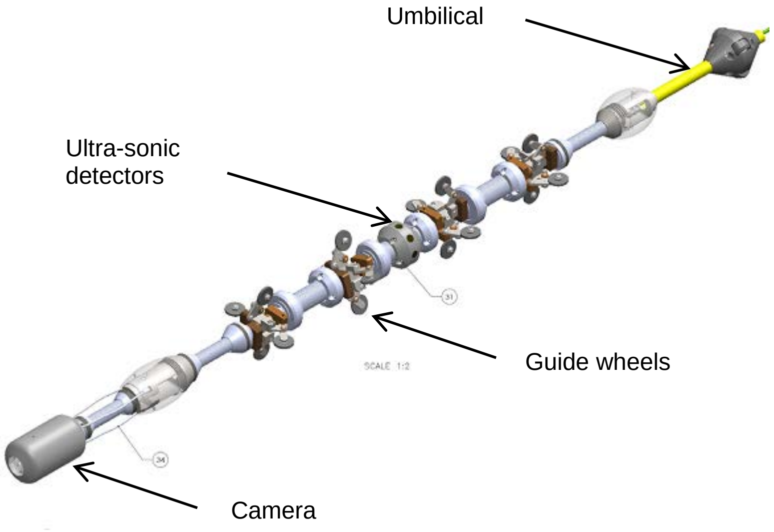

Figure 4: Schematic of Inspection Probe

The probe is inserted until it reaches the end of the coils within the evaporator and then slowly withdrawn, taking the circumferential measurements (on the order of thousands) as it goes. Figure 5 shows a coil thickness plot obtained using the inspection device shown in Figure 4.

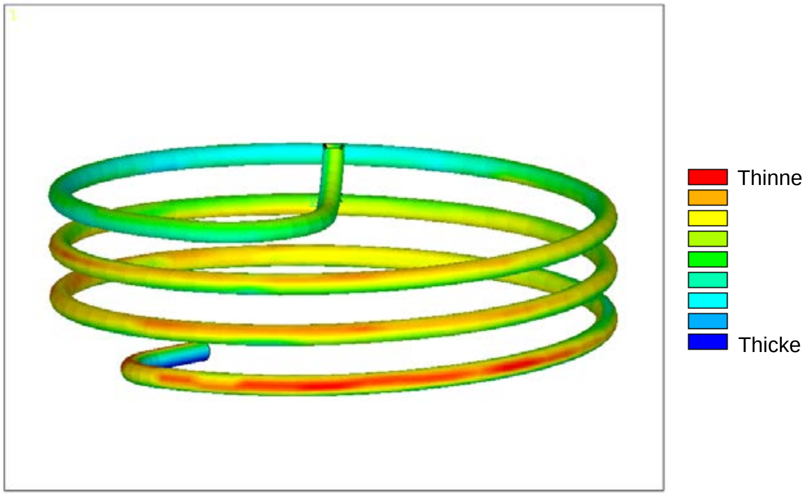

Figure 5: Wall thickness plot of lower coil helix example.

Corrosion equations

A successful series of coil inspection data was first collected in 2006. This physical reference point of the current condition of the coils enabled accurate calculation of corrosion rates of the coils. Subsequent routine inspections provides further data on changes to wall thickness enabling the corrosively of liquors to be refined and further defined.

Coil pressure data and liquor temperature

The most structurally onerous procedure during operation of the Evaporators is the heating and cooling of the liquor at different stages of the operational cycle. The temperature and pressure data is collated and processed in order to determine if the coil is in cooling mode, heating mode, loss of vacuum condition or not in use at that moment. A table of coil switching is then generated identifying when each coil switches and to which mode. A rainflow analysis is performed to identify the cycle types and their counts to be used for the stress analyses and subsequent fatigue assessment. This gives confidence in the cycle counting that is input to the fatigue assessment.

Experimental test rigs

Boiling rigs were developed to mimic HA evaporation processes and operated with a range of inactive simulants under evaporator operating conditions. The results of the tests fed into a bespoke thermal model incorporated with the FE numerical approach in order to predict corrosion into the future.

The experimental data generated by these test rigs is essential for the validation of the numerical approaches. A number of important observations were drawn from these such as predicting how the metal temperatures vary as walls thin due to corrosion.

PROCEDURE TO GENERATE THE 3-D FINITE ELEMENT GLOBAL MODEL OF COIL

Model geometry

A complete 3D model on one of the examined coils is shown in Figure 5. The coil is constructed of solid elements, using the actual geometry measurements taken by the ‘pig’ type probe at the time of the inspection. The circumferential wall thickness variation can be seen in Figure 6 and is due to factors including the stretching and compression of the walls as the coil was formed during manufacture and the cooling effect of condensate, which varies the corrosion rate.

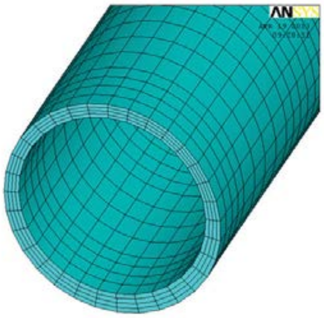

Figure 6: Model coil cross-section

Material modelling

A comprehensive materials testing program was performed to characterise the corrosion-resistant stainless steel properties of the analysed coils. Analyses are linear elastic and thus linear elastic material properties are used along with temperature dependant properties.

Mesh sensitivity study

A mesh sensitivity study was conducted to investigate how the mesh size influences the solution, in relation to accurate stress predictions. A region where high stress was predicted was chosen as shown in Figure 7. Comparisons between primary stresses, peak stress intensity revealed a difference of just 2.6%. Similar orders of variation were also shown for primary plus secondary stress, which are within acceptable bounds for this type of analysis. This allowed a suitable mesh density to be selected that provides an accurate prediction without using more computing resource than necessary.

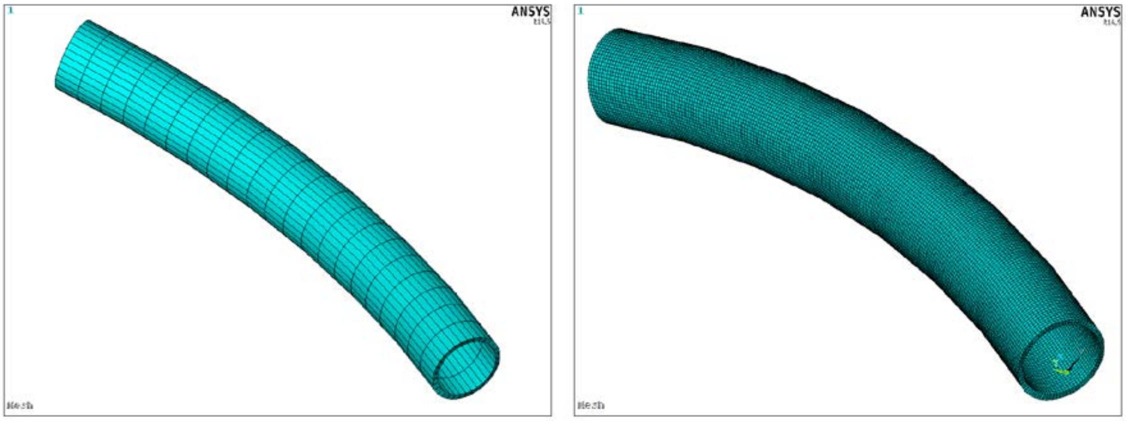

Figure 7: Element Plot of a Sub-Model of the Same Section from the Full Model

PROCEDURE USED TO PREDICT CORROSION INTO THE FUTURE

To model the progression of corrosion, each coil is thinned down to a series of minimum wall thickness profiles. The coil is thinned by the observed corrosion rate to date.

The calculation of wall thickness against time is performed via an iterative data exchange between ANSYS and a bespoke code developed by our in-house thermal modelling capability, shown diagrammatically in Figure 8. The initial geometry is firstly built in ANSYS using the inspection probe data, generating inner and outer wall diameters along the length of each coil. These are then ‘skinned’ to form a 3D geometry of the pipe and solid volumes for FE meshing. The wall thickness at each surface node is then calculated within the Finite element programme. The data is stored in two arrays – one for the bore and the other for the outer surface. This data is required later on during determination of the thermal boundary conditions and surface nodal temperatures that are the applied to the model. These temperatures are based on: steam temperature and pressure; wall thickness; liquor depth; and liquor temperature.

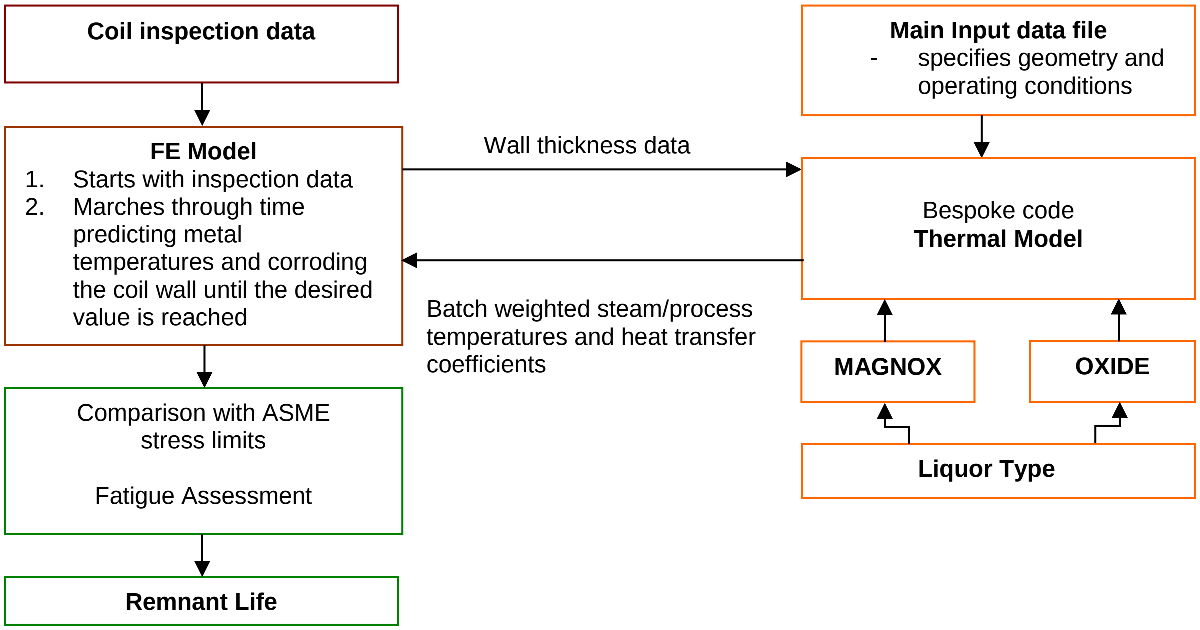

Figure 8: Future corrosion is predicted iteratively with the FE model code, ANSYS

A wall thickness data map is then transferred to the bespoke thermal model which is run and provides heat transfer coefficient data maps. This data is then mapped to the coil surface and a thermal analysis run is performed. This produces a temperature map on the coils from which the next corrosion step and thus geometry is calculated. The new coil geometry is made and the process repeats until the target minimum wall thickness is met. This process occurs under software control. A contour plot of a final coil wall thickness profile is shown in Figure 5.

MODEL VALIDATION AGAINST INSPECTION DATA

A series of model validation and sensitivity studies were conducted ensuring adequate accuracy was maintained in the FE models. These ranged from high resolution sub-models of key areas of interest to hand calculations of reaction force, stress and thermal checks.

The high resolution sub-models incorporated a higher resolution of probe inspection data of areas of interest. The required region was removed from the full model for each coil and replaced with the modified geometry. Displacements from the cut boundaries at each end of the sub-models were taken from the original full model for each operational load case.

A simple numerical validation demonstrating the capability of the FE modelling technique to conservatively predict future corrosion is presented below.
In this approach a previous inspection geometry profile of one of the coils within the HA Evaporator C was chosen, referred to as the reference case 1. After a period of operation, a new inspection was conducted referred to as reference case 2. Using the procedure described in the previous section, the reference case 1 was corroded into the future based on its operational time until the point at which reference case 2. This predicted wall thickness profile is referred to reference case 2 prediction.

The average coil wall thickness at a range of coil locations for the FE models of these were compared, shown in Figure 9. This plots the reference case 2 against reference case 1 (corroded into the future, in relation to operational time) referred to as reference case 2 prediction. This clearly demonstrates that this integrated FE model approach provides a robust analysis tool which conservatively predicts how this plant equipment will behave into the future.

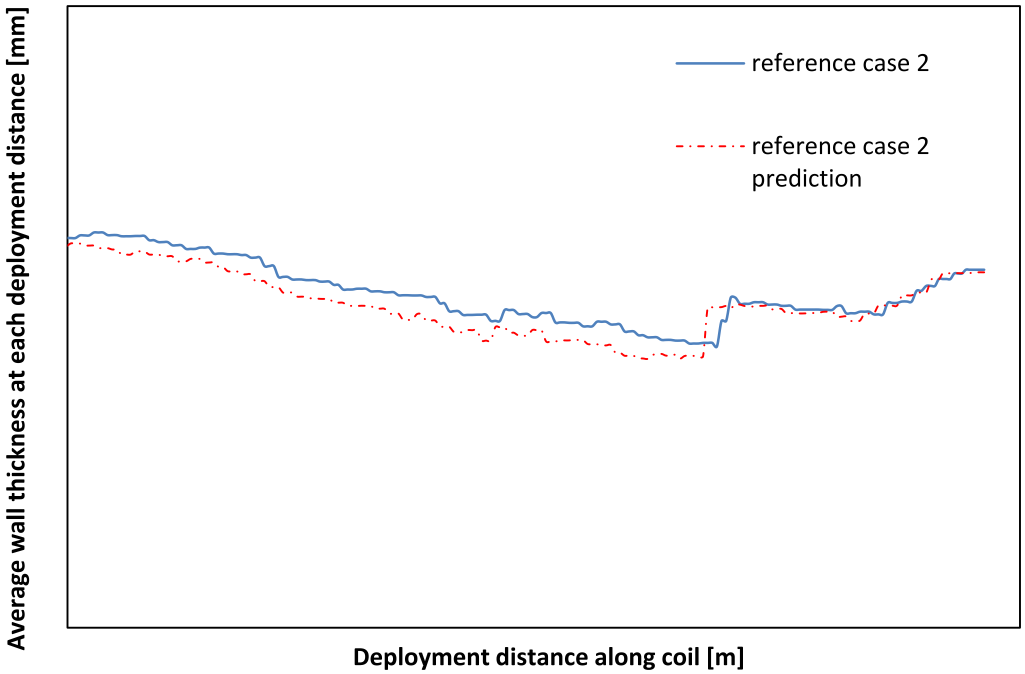

Figure 9: Comparison between the physical reference inspection profiles and the FE model predicted corrosion

OPERATIONAL FEEDBACK AND LESSONS LEARNT

Through continued inspection and assessment clear messages have been shown which have informed how the plant equipment has been operated and how preventative measures have been implemented to ensure continued safe operation.

One clear message is the value of condensate flooding. The coils are heated using condensing steam and so the evaporators have a certain level of condensate contained within them. Corrosion rates are known to be depth dependant due to increased surface temperature with pressure. A certain region of condensate is beneficial as this is expected to reduce operating temperatures within this region. As corrosion rates are strongly temperature dependant, this provides a benefit.

The overall length of the plant life can potentially be extended by extending each batch thus reducing the amount of cyclic loading on the coils.

CONCLUSIONS

It is concluded that this integrated approach provides a potentially power, robust analyse tool which has driven change and optimisation of plant procedures. This combined with on-going inspections enables safe continued operations whilst extending the life of the facility.

ACKNOLEDGEMENTS

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2. General Purpose Finite Element Analysis Code ANSYS version 14.5. ANSYS Inc. Southpointe 275 Technology Drive Canonsburg, PA 15317 USA.