



*Would the implementation of a risk based inspection strategy,
positively increase the statutory interval of a refinery furnace*

PSDM6019 Major project

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Summary

An internal examination of a refinery furnace was undertaken to conform to statutory regulations. Risk based inspection techniques were employed to identify and target specific damage mechanisms.

Planning and execution of the equipment outage was undertaken and documented via a milestone Gantt chart, commencement of the execution stage began on the 14th of October where specialist NDT techniques were deployed to identify and document extents of material loss, this was completed within an agreed timeframe of 21 days.

Subsequent analysis of results and calculation of tube remaining life, was undertaken via an API 579 and API 530 screening assessment. The outcome of the calculations found the future predicted remaining life of the tubes to be 44 years, providing justification for alteration to the equipment's written scheme of examination.

Recommendations to the future statutory interval of the furnace have been detailed, culminating in the extension of the current statutory interval from 24 to 36 months. Subsequent inspections conducted using the approach outlined in this review, provide scope to increase this further if found favourable.

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Abbreviations

API – American Petroleum Institute

CR - Corrosion rate

CTEMS - Commitment to excellence management system

FCCU - Fluid catalytic cracking unit

FTIS – Furnace tube inspection system

HSE – Health and Safety Executive

NDT – Non-destructive testing

PSSR – Pressure Safety Systems Regulations

RBI – Risk based inspection

SME – Subject matter expert

SOL – Safe operating limits

SPTC - Skin point thermocouples

Tmin - Minimum tube material thickness required for pressure containment

UHM - Unit health monitoring

VDU – Vacuum distillation Unit

WSE – Written scheme of examination

1.0 Introduction

The Valero Energy Corporation operates as a downstream petroleum manufacturer, marketing branded and unbranded refined products on a wholesale basis, primarily in the United States and Canada. Founded in 1981 Valero focuses its marketing strategy on the processing of industry undesirable heavy slate crude fractions, taking advantage of heavily subsidised discounted rates to gain a firm standing against its competitors and developing its organisational growth to a fortune 500 company. (Valero, 2017).

In 2011 Valero branched out from the continental United States purchasing the Pembroke Refinery in Wales. After the acquisition of the plant, Valero invested extensively into the alkylation, vacuum distillation and crude facilities of the refinery, increasing its throughput from 195,000 to 295,000 barrels per day. With the geographic assets of deep-water marine jetties, cross country high volume pipelines and an established network of road and rail, the refinery is used as a gateway to the domestic market of the United Kingdom, the European Union and as a dynamic competitor supplying the US East coast and Atlantic basin.



Figure 1: *View of Pembroke refinery from the south* (Valero, 2017)

2.0 Background information

2.1 Regulatory frameworks of fixed equipment inspection

Governing regulations associated with the requirements of mandatory inspection and the continued safe operation of equipment, vary greatly from one jurisdiction to another on both national and an international scale (Bragatto, 2016). In the United States of America this is enforced by the Occupational Safety and Health Administration, however due to the refinery assets being located within the United Kingdom, the Pressure Systems Safety Regulations (HSE, 2000) take precedence. The regulations stipulate that *“the duties imposed by PSSR relate to pressure systems for use at work and the risk to health/safety. The aim of these Regulations is to prevent serious injury from the hazard of stored energy as a result of the failure of a pressure system or one of its component parts”*.

At Pembroke refinery the PSSR regulations are implemented by the Inspection department who act as a ‘*User Inspectorate*’ (HSE, 2000) registered body that has the authorisation to undertake conformity assessments. My role within the refinery structure is an Inspection Engineer, employed by the client but acting as a stand-alone entity to ensure the compliance with UK legislation. This role has a unique responsibility to balance the operational needs of the business and the safeguarding of personnel and equipment, through confirmation of equipment mechanical integrity.

Traditionally internal inspections of equipment to satisfy the PSSR’s have been conducted at set intervals. These mandatory inspections, are undertaken often at times when profit margins are already narrow and are perceived by the refinery owner as an inconvenience and a disruption to normal steady state operation.

In 2008 the UK PSSR regulations were amended to include the comment that statutory inspections *“shall be set at fixed intervals or determined using a justified sound engineering approach”*. (HSE, 2008)

A justified sound engineering approach has since taken the form of the technique of risk based inspection, which is the explicit use of a dynamic risk assessment to plan, justify and aid the analysis of results from inspection, testing and monitoring regimes. The technique offers the opportunity for inspection focus and prioritisation, which looks to reduce both risk exposure and inspection/downtime cost.

In October 2019 I undertook a statutory internal inspection of a product fired heater on the vacuum distillation unit. The current situation, based upon the older PSSR, operates on a fixed interval basis of 24 months at a cost of approximately 300-400 thousand pounds per outage (when labour, costs and unit down time are factored). Applying a risk based inspection approach, provides technical justification to allow for the probability risk level to be reduced according to the outcomes of targeted NDT inspection and subsequent component lifespan calculations, mitigating the potential mechanisms of degradation.

The resulting outcome of the risk based analysis would not remove the risk but will however, reduce the level of overall risk to a more tolerable or insignificant factor. This in turn may allow for an extension to its statutory interval based on sound engineering practices benefiting the business both operationally and financially.

(Hall, 2019)

3.0 Vacuum distillation process (VDU)

The VDU is designed to remove gas oil fractions from a reduced crude feedstock to provide a low carbon and low metal content feedstock to the fluid catalytic cracking unit (FCCU). These carbon compounds, or asphaltenes and metals, are undesirable to the FCCU feed streams due to the high potential of lay down coke on the catalyst. (Valero, 2015)

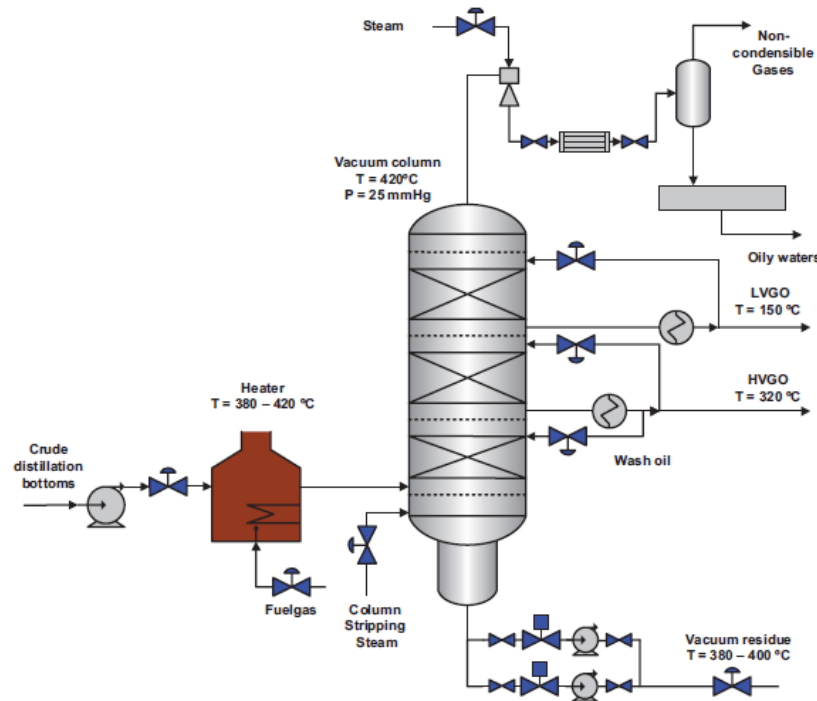


Figure 2: VDU process flow diagram (Parkash, 2003)

To achieve the desired feedstock, hot atmospheric residue is received from the adjacent crude distillation unit mixed with cold residue from tank storage feed the VDU. The variations in viscosity, PH levels and chlorides are at this point blended to ensure a steady homogenous feed through two parallel heaters with 8 flow passes. The then partially vapourised raw product enters the flash zone of the 70m tall column under vacuum conditions, where it is separated into more profitable products (**Figure 2**). The process relies on the heating element of the furnaces to provide the necessary separation within the column.

3.1 Furnace fundamentals

The refinery furnaces are equipment assets comprised of a number of components, designed to burn fuels efficiently, transferring the heat of combustion to the raw product in preparation for the fractionating process. This heat transfer is accomplished by conduction, convection, or radiation (Brumbaugh, 1984). The capacity of the two furnaces to the vacuum distillation column allow for a process rate of $\sim 640\text{m}^3/\text{hour}$. Raising the temperature of the feed slate from 60°C where it enters the furnace from the blending drum, to where it leaves at $\sim 390^\circ\text{C}$ ready for piping to the fractionator.

The furnace consists of an insulated firebox, in which natural gas is burned as fuel, and ducts that transport the combustion gases away to a stack. The raw product being heated within the furnace is piped back and forth through an array of passes within the firebox, heat is absorbed as the product travels through this network (**Figure 3**).

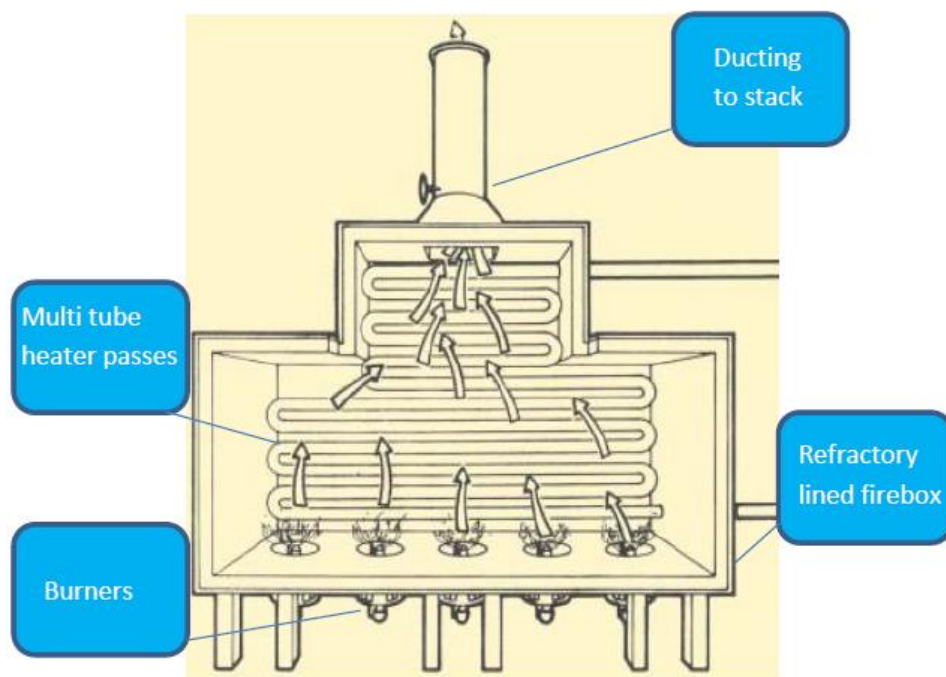


Figure 3: Components of a furnace Image source: (Brumbaugh, 1984)

(Hall, 2019)

4.0 Identifying the problem

An inherent problem lies with applying a fixed inspection interval mentality to satisfy the Pressure Safety Systems Regulations. The repeated cyclic maintenance activities of bringing the furnace out of service, coupled with moisture ingress and the vibrations/stresses involved with returning the furnace to service, can often have an increased detrimental effect to the mechanical integrity of the equipment. Industry has comprehensively documented the extent and causes of furnace failures identifying that improved equipment reliability and stable operation are most likely achieved by the reduction in the susceptible mechanisms that result in tube failures.

An inference can therefore be implied that in order to ultimately understand a failure, it is essential that the internal mechanisms are fully understood and successfully mitigated. It is this area of specific equipment awareness and identification of limitation that becomes a fundamental flaw in a fixed interval inspection regime.

Industry research has established that while the components of fossil fired furnaces have a theoretical useful service life of 30 years or more, actual tube life in practical scenarios can range from 24 months to 100 years plus. This can be attributed to the intensity of detrimental material loss enacting within the tubes leading to unforeseen failures. Most notably the combination of localised high temperatures due to flame impingement, and the internal corrosion of the tubes resulting in rupture. However it can be argued that if a corrosion deterioration trend can be established and tracked, the probability of failure is significantly reduced to a tolerable risk. It can therefore be deduced that in practicality it is the understanding of the susceptible corrosion mechanisms and the rates at which material losses occur in a particular furnace system that is essential for failure prevention and the basis of future equipment outages.

With plant equipment inevitably deteriorating with age, refinery owners from both a safety and business loss perspective, become highly vested in the successful prediction of the tube's remaining life and the potential of quantifying material integrity to ensure a successful return on investment.

It can therefore be justified that obtaining multi-disciplined data from new and extensive non-destructive techniques is essential for the successful identification of mechanisms and the calculation for probability of failure. This can be theoretically achieved through the utilisation of existing data indicators and analysing the historical records of furnace design drawings, process parameters and previous inspections; providing a justifiable stance from which to ascertain the most susceptible elements to establish the extent of deterioration and formulation of preventative maintenance. Approaching the issue in this manner results in a new monitoring regime that does not rely upon the limitations of fixed interval internal inspection, one that is both conducive to the dynamic needs of the business as well as satisfying the requirements of the UK pressure systems regulations.

(Hall, 2019)

5.0 Consequences of furnace failure.

The Industry case studies of Exxon Mobil (ICIS, 2000) and a reactor Feed Furnace (Wu, 2019) have shown the devastating consequences that loss of containment can have on both the safety of the workforce and equipment integrity. The resulting investigations found that in both cases the tubes of the furnace were subjected to both fireside and internal corrosion issues. It was also found that the refractory that normally protected the furnace structure from the extreme temperatures of the fuel burners had significantly deteriorated, resulting in localised metal loss of the tubes due to scale and erosion thus increasing tube-wall stress and ultimately leading to failure. Whilst the implications of loss of life is incalculable, the loss of the equipment from a business perspective results in a lost profit opportunity of one million pounds per day from product processing alone; not including the unspecified costs of repair and penalty which would result from such a failure. **Figures 4** and **5** below show evidence of tube ruptures that occurred in an explosion at a Styrene Plant in Taiwan.



Figure 4: *Tube rupture* (Babcock & Wilcox, 2017)



Figure 5: *Furnace distortion* (Wu, 2019)

6.0 Furnace susceptible damage mechanisms.

Considering historical cases of furnace failures in industry and the identification of contaminate processes that exist within operation, it becomes evident that the following mechanisms can be grouped into four distinctive causes:

6.1 Erosion

Erosion within furnaces occurs from the effect of accelerated removal of surface material by solids in the form of particulates held within the burner flue gas streams. The particulates impact against the furnace tube walls, resulting in a constant abrasion that removes any present protective scale. This in turn exposes new metal surfaces and repeats until the pipe is thinned until a critical pressure containing point is reached in the tube wall thickness.

Commonly a furnace's erosion centres on the formation of slag and coke, these entities are often visually detectable or can be identified through NDT techniques. The mechanisms are caused by a reaction between flue gas ash particles and the furnace material composition. **Figure 6** is an example of witnessed slag formation causing increased erosion particulates. **Figure 7** shows localised coking and the use of thermographic surveys to highlight defects.



Figure 6: *Slag formation* (Noble, 2018)

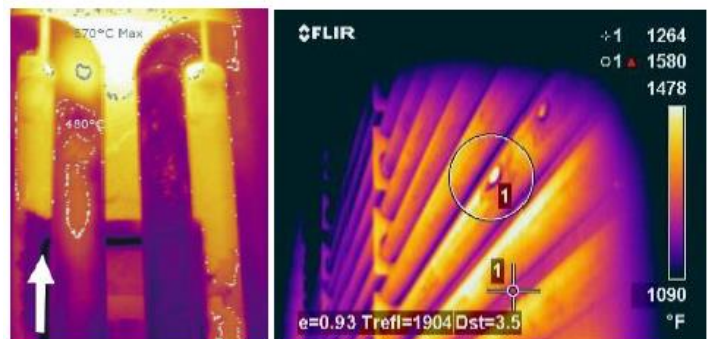


Figure 7: *Coke laydown* (Noble, 2018)

6.2 Corrosion

Corrosion issues within refinery furnaces are personified by the loss of material thickness through chemical reaction, this can be induced through the presence of sulphur and hydrogen sulphides held within the process streams resulting in general material thinning; however commonly material loss is categorised by pitting formation. Pitting corrosion produces highly localised cells of galvanic corrosion, where the pit itself becomes a cathodic driver and the surrounding material anodic. Diffusion of ions between the pit and tube interface is significantly limited resulting in the acceleration of material loss to the point of through wall failure. API 571 (2011) gives guidance on areas most likely effected by pitting corrosion stating that bends, changes in section and structural discontinuities are highly susceptible to this type of damage mechanism. **Figures 8 and 9** show evidence of historical pitting issues of the refinery's furnaces.



Figure 8/9: *Tube failure due to accelerated erosion*

6.3 Stress mechanics

Internal stresses within the components of the furnace are of critical importance when calculating mechanical integrity. When considering stress mechanics of failure, the critical factors of geometry, stress raisers (such as bends and welds) and operational conditions, arise from the mechanical loading and potential threat of thermal cycling of the tube material. Importantly API 571 (2011) highlights that start up and shutdown activities can greatly increase the susceptibility of thermal tube fatigue.

Conducting a thorough visual inspection will in the majority of cases, highlight areas of significant deformation. This has been evidenced through previous inspections of equipment where it has been identified that tubes have undergone short/long term overheating. Short term overheating manifests itself in the form of physical bulges (**Figure 10**) within the pipe wall resulting from excessive localised heat input from the furnace combustion process. Long term overheating can cause significant tube wall failure (**Figure 11**) from prolonged temperature excursions, above the safe operating limits (SOL) of the tube material properties.

In both cases mechanical repair of sections is required to ensure the integrity of the pipe wall structure is maintained.



Figure 10: *Tube bulge* (Babcock & Wilcox, 2017)



Figure 11: *Tube rupture* (Babcock & Wilcox, 2017)

6.4 Metallurgical mechanisms

The presence of creep becomes increasingly critical at the operation of higher temperatures. Metals stretch when subjected to stress, when at low temperatures tube life expectancy to failure is not a factor. However at high temperatures, applying stress at points considerably below a given yield stress can cause a material to continually stretch for as long as the stress remains applied. The refinery heaters operate at a maximum of 620°C, during normal operation consistent temperatures can be recorded ~610°C. **Table 1** below highlights the significance of minor temperature excursions beyond design limits in tube life expectancy, should the onset of creep be present within the furnace. **Figure 12** show the resulting cracking defects when loss of containment has occurred due to the creep mechanism.

Temperature	Creep Life
900°F (480°C)	64,194 Years
1100°F (595°C)	58 Years
1150°F (620°C)	13 Years
1200°F (650°C)	3 Years
1250°F (675°C)	323 Days
1300°F (705°C)	94 Days
1400°F (760°C)	10 Days
1500°F (815°C)	1 Day

Table 1: *Temperature vs creep life* (API, 2011)

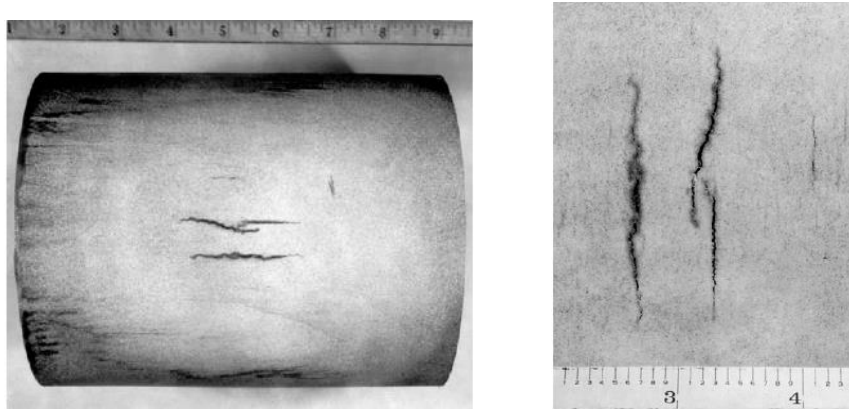


Figure 12: *Creep cracking* (API, 2011)

7.0 Addressing the Situation

Risk based inspection(RBI) techniques are defined as the explicit use of a dynamic risk assessment to plan, justify and aid the analysis of results from inspection, testing and monitoring regimes. The technique offers the opportunity for inspection focus and prioritisation, which results in both the reduction of risk exposure and inspection/downtime cost.

The risk based inspection approach centres on the principles of the Fuzzy logic inference system developed in 1990 (Jang, 1991) (**Figure 13**) and later adapted to encompass a probability vs consequence matrix of risk analytics, (**table 2**) use of the system enables mitigating subjective judgments based upon a specific set of information gained through targeted inspections and the collaboration from input process variables.

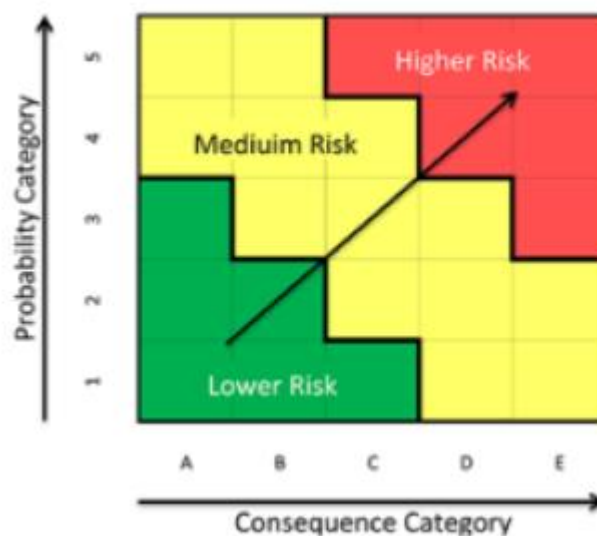


Figure 13: *Probability vs consequence matrix* (Modern Refractory INC, 2018)

When formulating a risk output two scales of ranking are critically considered. Firstly the consequence level of risk is ascertained. This is achieved through a multi-disciplined team using the following facets that can be summarised into four topics:

- Subject matter expert (SME) Judgement.
- Cost/Loss profit calculations
- Statistical data
- Consequence estimation (whether it be safety, economic or environmental)

Secondly probability observations are calculated, the risk category judgments are based on acute functions that when used in collaboration, can pro-actively benchmark the likelihood of events to occur. These once again can be summarised into four topics:

- Opinions of subject matter experts (SME's)
- Corrosion calculations
- Inspection data
- Mechanism estimation models.

The use of the Fuzzy logic inference system, coupled with the correct input variables can effectively categorise the risk of equipment and even specific components within varying pressure envelopes.

The Valero risk inference matrix detailed in **table 2** below, demonstrates the scenario that the refinery furnace presents, where it is deemed an unacceptable level 2 risk and therefore a mandatory fixed interval inspection of 24 months is applied. Justification of this banding arises from considering the consequence ranking, where it has been established that a loss of the asset would pose a business impact of one million dollars a day placing it into a level 3 category. Due to the lack of results and information as to the extent and trend of damage mechanisms within the furnace, a likelihood of banding E (likely to occur) can only be applied.

									
Business	Safety								
>\$100 Million	>10 Fatalities On Site or Multiple Fatalities Off Site	VI	TR	Level 1	Level 2	Level 3	Level 4	Level 4	Level 5
>\$10MM to \$100Million	2 to 10 Fatalities On Site or One Fatality Off Site	V	TR	TR	Level 1	Level 2	Level 3	Level 3	Level 4
>\$1MM to \$10MM	Permanent Disabling Injury (e.g. Amputation) to Single Fatality	IV	BA	TR	TR	Level 1	Level 2	Level 2	Level 3
>\$100K to \$1 MM	Serious Injury to Permanent Injury (e.g. Burn)	III	BA	BA	TR	TR	Level 1	Level 1	Level 2
>\$10K to \$100K	Recordable to Lost Time	II	BA	BA	BA	BA	TR	TR	Level 1
<\$10K	Minor to First Aid	I	BA	BA	BA	BA	BA	BA	TR
Likelihood			AAA	AA	A	B	C	D	E
Qualitative description			Rare - equivalent to being killed by a lightning strike.	Remote, has occurred once or twice in the Industry	Unlikely that the event will occur at this facility.	Conditions may allow the event to occur within industry using similar technology	Conditions may allow the event to occur at this facility during its lifetime	Likely to occur at this facility once every 10 years	likely to occur
Scenario frequency per annum			10-7 to 10-6	10-6 to 10-5	10-5 to 10-4	10-4 to 10-3	10-3 to 10-2	10-2 to 10-1	10-1 to 1

Table 2: Valero Risk inference matrix (Valero, 2017)

Whilst the consequence categorisation will not alter from a level 3 banding, the deployment of a risk based inspection approach according to outcomes of targeted NDT inspection and subsequent calculations, if found favourable, will allow for the likelihood level to be reduced; Establishing a trend for current and future potential mechanisms of degradation.

The additional cost that the in depth specialist techniques would entail by using risk based analysis, would be insignificant when considering a return on investment, if the interval of the internal inspection was to be increased. It is important to note that the use of an RBI approach does not remove the risk but will however, reduce the level of overall likelihood to a more tolerable and acceptable factor. The extension to statutory inspection intervals based on sound engineering practices would then be justifiable to both the HSE and PSSR.

(Hall, 2019)

8.0 Aims and Objectives

The following aims and objectives can be outlined for the successful assessment of a refinery furnace and transition from a mandatory fixed interval examination to a risk based inspection approach:

- To create a written scheme of examination for the refinery heater and to develop an inspection test plan strategy to satisfy the data gathering necessary for risk based analysis, with due consideration given to applicable safety aspects that will look to assess and quantify the risk of operating a specific furnace over time.
- To successfully coordinate, plan and execute the internal inspection of a refinery heater on the vacuum distillation unit.
- To analyse the resulting data using a combination of industry approved API codes and a sound engineering approach, providing justification for re-assessment against the Valero risk assessment matrix.
- To formulate recommendations from technical analysis, to better guide the owner-user to plan examinations based on consequence and likelihood of potential mechanisms.

It is the ultimate objective that a modern inspection strategy can shift dispensations away from the current approach of fixed interval inspections, towards a more flexible and technically grounded analysis.

9.0 Written scheme of examination (WSE) and development of inspection strategy

Before an effective strategy could be formulated, a thorough review of the furnace design drawings, data sheets and historical records was made (A summarised version of the review can be found in **Appendix 19.2**). The empirical data resulting from this process was essential to become familiar with the heater type, known past problems, existing corrosion control issues and the extent of previous repair history. The review identified a basic WSE (**Appendix 19.3**) that had been used in previous shutdowns, incorporating these pertinent points from the historical WSE provided the foundation of a new written scheme framework.

To address identified gaps in the design review, a meeting was then conducted between inspection and the refinery corrosion and process engineers; process streams were discussed and their potential for manifestation into degradation mechanisms. The result of the collaboration between departments allowed for the specification of relevant mechanisms for addition to the WSE, with the review completed the newly drafted written scheme of examination to satisfy the PSSR was assembled (**Appendix 19.4**).

In order to develop an effective strategy, the furnace can be broken down to individual components for assessment, API codes 579 (Fitness-For-Service (FFS) assessment (2016)), 580 (Risk Based Inspection (2014)) and 571 (Damage mechanisms (2011)) were used to provide guidelines in specifying the extent of inspection work scopes:

9.1 Tube supports

Hangers and supports shall be visually inspected looking for signs of distortion, cracking, oxidation, scaling and corrosion. The supports should be in position and not obstructed from expansion during cycles of heating and cooling. Previous inspections have highlighted that support casings are extremely brittle at ambient temperatures, care will need to be taken when handling. Evidence of cracking and distortion may indicate the presence of creep and limited remaining mechanical integrity.

9.2 Burners

Visual inspection of surrounding refractory must be undertaken to identify potential adjustments to a burners flame pattern. Burner tips and gas heads must be checked for plugging/ corrosion and cleaned as necessary. Burner blocks and air registers must be assessed for alignment and clearance from surrounding support structure. Once the furnace is returned to service, follow up inspection using Infrared technology to ensure continued safe operation is recommended.

9.3 Casing

Inspection shall be undertaken internally for refractory damage and damage to casing. Historical records from on-stream monitoring show potential areas of casing degradation, these should be investigated and repaired during the outage. Use of a third party refractory expert is recommended and is to include close examination of the following areas:

- Cracking or loose sections of brick/ castable fibre that may have dislodged during operation.
- Unevenness / buckling of the furnace floor, crazing/ shrinking of burner blocks.
- Corrosion of steel casing, refractory anchors and support bolting.

9.4 Tubes

Careful attention must be paid to inspect all tubes for bulges that may have resulted from hot spot flame impingement. Bulges can be most likely attributed to high temperature yielding or creep, therefore measurements of suspect areas must be taken using a dial/ring gauge. Recommended maximum bulging limits as specified for the design code is 5% for carbon and low alloy steels, if bulging exceeds this limit the tube should be retired/repared. Heavy scaling on the fired side of the tube may indicate evidence of localised hot spot or overheating issues. Overheated tubes may also exhibit excessive sagging. Where excessive scaling is noted, remove the scale and ascertain measurement thickness of the location.

Due to the data requirements of remaining tube life calculations it is recommended all tube passes of the firebox are intelligently pigged. The use of the advanced tube inspection technique will be to firstly de-coke the internal surface of the tubes, allowing for ultrasonic inspection to detect and detail general wall thinning, as well as internal and external anomalies caused by corrosion and erosion mechanisms. Additionally geometric anomalies such as ovalities and dents can be both detailed and located. Information as to how this technique works, the potential resolution of data and a summary of the technique limitations can be found detailed in **appendix 19.6**.

Work scopes for completing the component action items are compiled and further detailed into a technical inspection pack for distribution to the outage planners. This created document is demonstrated in **appendix 19.5**

9.5 Additional data gathering

For successful completion of the remaining life calculation in conjunction with the results from the process of intelligent pigging, accurate and frequent tube wall temperature measurement is of vital importance towards the understanding of tube life and efficient furnace operation. A review of the historical temperature records was achieved by collating raw data from the furnace skin point thermocouples (SPTC) highlighted in the design review and general arrangement drawings **appendix 19.2**. SPTC's are used to provide continuous data on furnace temperatures and are stored digitally in an archive dating back to 2001, an example of the output graph given by the SPTC is demonstrated in **appendix 19.7**. Due to the lack of temperature records for the 22 years of furnace life preceding 2001 a conservative safe operating limit of 620°C is used.

9.6 Costing Justification.

Furnace internal inspection currently operates on a fixed interval basis of 24 months at a cost of approximately 520 thousand pounds per outage (when labour, costs and unit down time are factored) a basic breakdown of costs is detailed in **Appendix 19.8**. The figure includes the additional cost of fifty thousand pounds for the advanced tube inspection technique. Having justifiable scope to increase the inspection interval by a preliminary figure of 12 months to a 36 month interval, has the potential of saving the refinery ~1 million pounds over a 10 year period. This costing assessment was presented to the business complex managers who authorised the added expenditure of including the advanced tube inspection within the statutory work scope. Form TR597 demonstrated in **Appendix 19.9** documents this process.

10.0 Project Planning

With the inspection strategy formulated, approval was gained from the Chief refinery Engineer to proceed. A series of meetings were held with the planning and economics department to construct a time frame when the heater could be removed from service with minimal financial and process consequence.

The refinery planning and economics department identified that due to the margins of heavy slate crude during the month of October 2019, the required duty from the vacuum distillation heaters would be reduced. This window of limited crude oil cycling presented the most favourable moment to remove a single furnace whilst leaving its partner furnace in service. A date of the 14th of October was subsequently set for a period outage of 21 days. Due to the requirement of non-term contractor inspection techniques, ones that were not readily available on site, planning for the outage began immediately. From the outset it was necessary to develop and scope all inspection resource that would be required, this included requests of tender from third party organisations and securing the availability of the specialist NDT techniques from companies that had the ability and equipment to achieve the desired results. Critical time management was required to ensure that this was accomplished ready for the outage timeframe, making sure that effective correspondence, communication of task and the answering of technical queries was completed in an organised and timely approach to overcome various obstacles that would inevitably arise in the logistics of outsourcing inspection work to entities that the refinery had not previously used.

To coordinate and track the efforts in the lead-up to the furnace inspection, a high level Gantt chart was constructed to monitor the progress of the outage through to completion. **(Figure 14).**

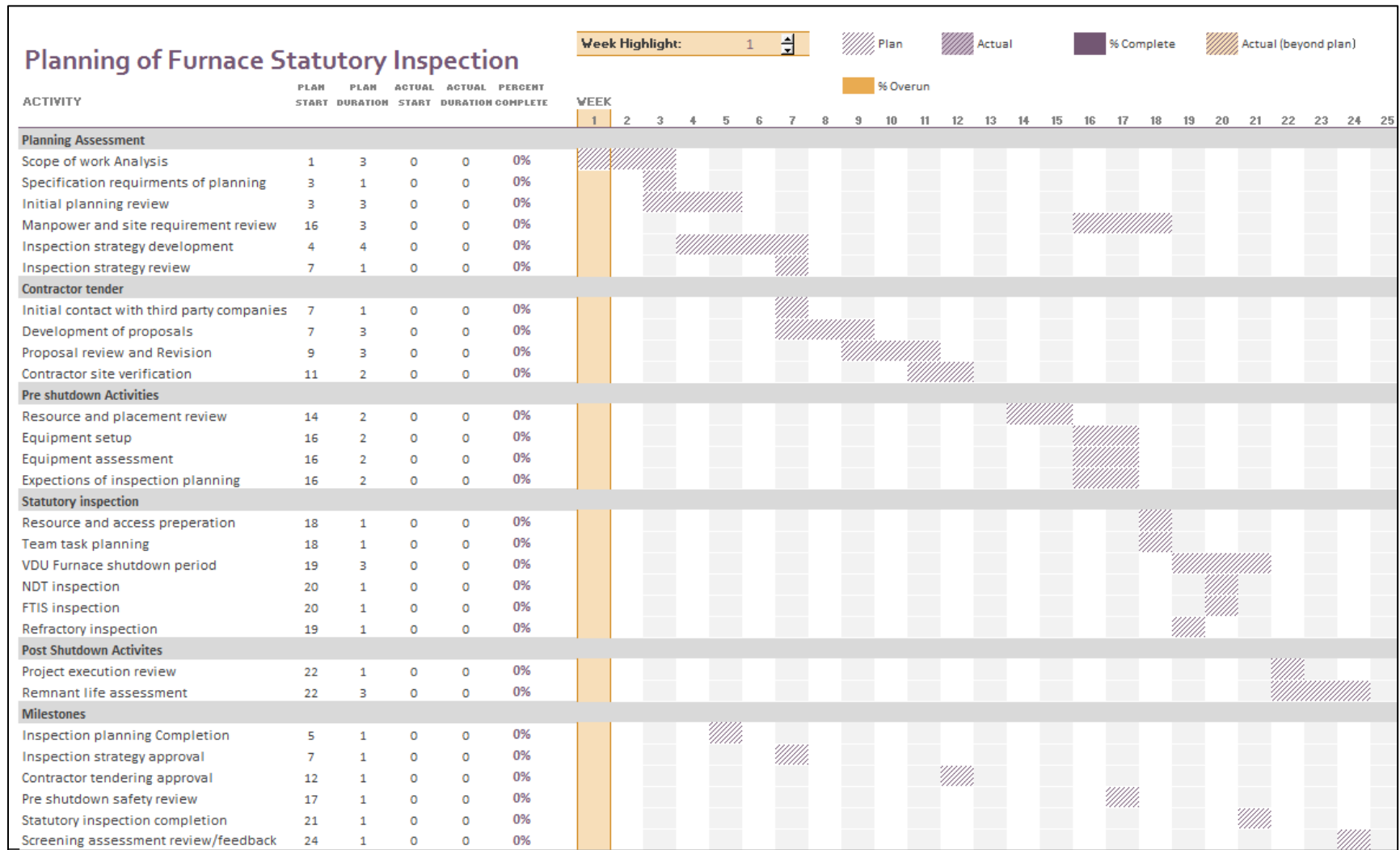


Figure 14: CDU overhead planning Gantt chart.

10.1 Review of Gantt chart

Consideration of the crucial elements of the Gantt chart show that the timeframe of operations can be dissected into three specific stages: planning, execution and analysis. The success of all of the milestones depends on the communication, management and co-ordination of personnel involved. Due to the statutory nature of the outage, my responsibility was the lead role in organising and coordinating the various elements. The goals in the planning stage of the operation were achieved through a weekly progress meeting, where the different departmental teams were gathered to provide an update as to the development of each lead up task. During this time I worked closely with the refinery planners to develop a Primavera resource plan for the mechanical execution of the outage. Managing the milestones in this way, gave an advantageous oversight to the outage completion making it easier to identify potential threats and vulnerabilities before they became a logistical issue.

During the initial stages of the planning it became apparent that the task of enlisting third party contractors from areas not local to the refinery, was not a straight forward undertaking. For example the intelligent pigging company AHAK based in the Netherlands, communication in English proved problematic when preliminary contact was made and expression of work scope became difficult when attempting to convey the requirements of inspection. As the relationship became more developed between myself and the lead specialist Engineer, approaches to gain understanding and the use of better and effective methods of communication were employed to achieve a successful tender document. The increased time that it took to complete the authorisation to operate status, was able to be absorbed within the early stages of the operation.

As the operation moved towards execution the float in the Gantt chart significantly reduced, in order to mitigate the potential threat of milestone overrun, I dedicated increased focus and time to managing the outstanding actions to allow for timely completion before the statutory inspection began. An example of this is demonstrated through the use of the specialist refractory inspector. Due to the early identification of time constraints during the execution phase of the inspection, the timing of the specialists' arrival was brought forward to complete as much on-stream inspection as possible, the result of this, lightened the work scope during the event and provided critical extra hours should one of the other inspection processes exceed their allocated slot.

10.2 Contingencies

Significant consideration was given to planning for contingencies during the initial stages of planning. The main concerns being budgetary and resource consequence, examples of such included the potential for mechanical and inspection task overrun, where equipment rental cost as well as labour and mobilisation/demobilisation cost increases due to extended use. To mitigate the financial impact of executional time delays, a 30% budget contingency was secured from the outage managers. Additionally an inter-departmental task force was established consisting of inspection, mechanical, operator and planning representatives to daily assess and review the current standing of ongoing progress, with the hope to highlight potential threats and issues early, to avoid extended delays to the current plan.

Anticipating the possibility that defects may be highlighted by inspection activities, additional repair hours were factored into the execution phase, whether a repair was necessary or not, the extra hours allowed for potential task overrun issues, to be absorbed without significant impact to the overall time frame.

11.0 Execution phase: team formulation

As the project entered the early execution phase, challenges arose as to the most effective approach to resource and manpower allocation. I began by addressing the issues at the earliest opportunities to ensure a smooth transition towards beginning the statutory inspection of the furnace. During this time I assembled the leading team supervisors to discuss and formulate a working shift and break time schedule, which would provide for a satisfactory working and rest balance, one that would allow for the successful completion of execution milestones and compliance with the company's safe working practices. In addition to overseeing the third party specialist inspection activities I had direct supervision over a team of term contracted NDT technicians for the outage. For the secondment of these technicians from their scheduled day to day duties, I had to manage and align ongoing work tasks to ensure participation in the outage and roles that I deemed necessary.

11.1 Lead engineer responsibilities

During my time as unit inspection engineer I have been responsible for many minor statutory inspections of refinery equipment, the inspection of a furnace presented a multi-component challenge that I had not previously experienced. I approached the task however, with the same approach from knowledge I had gained from my previous experience. The main elements of which involved spending time in the field observing the work undertaken, being consistent with my expectations of what was to be achieved, and actively supporting and communicating the refinery's site safety policies, procedures and job aids. I ensured the refinery's important mantra that "*safety is the foundation of success*" became the elemental motivation in any task that was undertaken during the outage. When expressing my expectations to my team and specialists I focused on the following qualities to ensure a successful execution of the proposed scope of work.

11.1.1 Development of execution strategy – From the outset of receiving an accepted tender document from the various specialist contractors I took the time to personally meet each of the supervisors on site where the inspection was to take place, this process allowed me to convey the exact requirements of the task and my expectations of what pre execution work would be required. These site meetings gave the opportunity to receive feedback from the supervisors, where they were able to give guidance on the feasibility of what was to be undertaken and identify any potential issues before the task was to begin. Operating a pre-emptive approach in this manner allowed for successful mitigation of items that may have caused significant time delay once the outage began. From the outcomes of these meetings I was also able to foster an enhanced working relationship between myself and each of the supervisors, an element which would be greatly beneficial once the execution began.

11.1.2 Communication of clear instruction – To enable the successful coordination of inspection activities, communication between myself and the various teams was of paramount importance. This I achieved using morning and afternoon daily meetings with the objective of effectively conveying what tasks had been completed and the priorities of the next work scopes to be undertaken. During these meetings, safety awareness and safety issues were discussed and again reinforced as to their continued focus, the points raised from these meetings the supervisors took on board for actioning by their teams. Having the various disciplines together on a regular basis gave sufficient opportunity for the accurate update of information and importantly feedback from the varied work teams. Managing four different contractor teams from a range of technical and geographic backgrounds required comprehensive communication, this I achieved using the aids of site visits, progress oriented meetings, email and telephone calls.

11.1.3 Daily operational tasks – Early In the execution phases I employed a hierarchical structure of management and task delegation. I identified a senior representative from each of the companies to direct and supervise their given teams for the completion of their specialist tasks. Organising the structure of authority in this manner enabled for the teams to operate in a semi-autonomous approach, whilst still allowing for oversight of performance and operational progress through the feedback received from the team leaders and the shared handover logs kept between one shift and the next. With inspection activities ongoing throughout the entirety of the furnace outage it was my responsibility to inform both the mechanical and planning lead directors of the group's progress. This was achieved by holding a high level meeting once the daily shifts activity had been established. This co-ordinated approach allowed me sight of other activities that were being undertaken in other departments, limiting the possibility of resource conflict and allowing for the smooth transition from inspection to the return to service by mechanical de-blinding and start-up operations.

11.1.4 Identification of skills necessary to complete the inspection – Whilst I hold the qualifications to perform the visual internal inspection of the furnace, I do not have the expertise and experience to conduct the specialist techniques required for the RBI data gathering. For this reason I researched and outsourced tasks to provide the information I required for analysis. These were third party groups that I had worked with in the past on different projects, the breakdown of skills and teams can be categorised into the following:

- Intelligent USTM Pigging (FTIS) – AHAK Industrial Services (47yrs industry experience)
- Refractory Inspection – Refline limited (45yrs industry experience)
- Metallurgical inspection – Oceaneering inspection (30yrs industry experience)
- Non-destructive testing – CAN offshore Ltd (25yrs onsite experience)

11.2 Organogram for the Inspection team

The organogram below shows the hierarchy of operational structure.

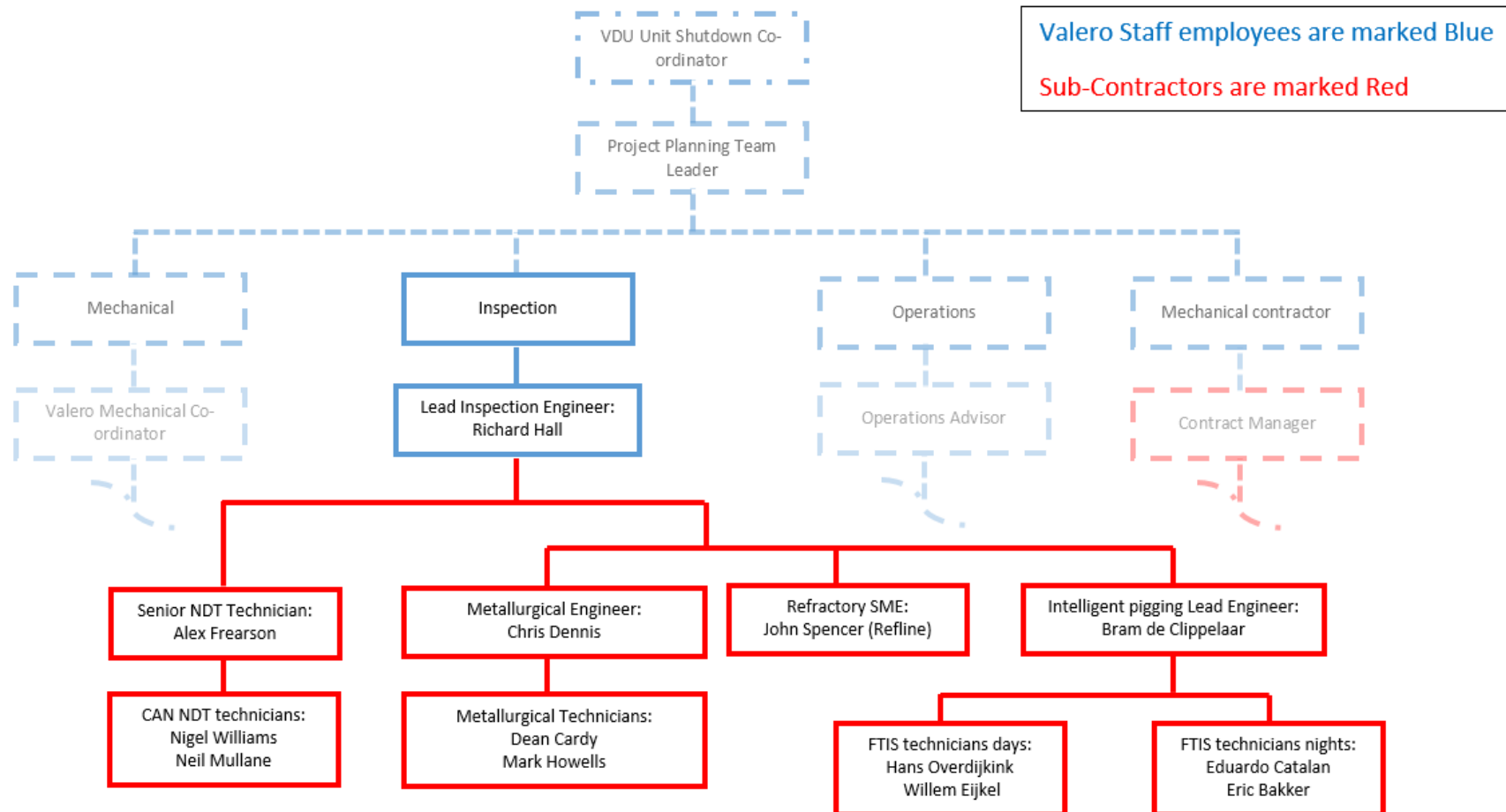


Figure 15: Inspection Organogram

12.0 Execution phase completion.

With the planning, maintenance and operations activities all completed ahead of the execution phase, it became a straight forward transition to begin the preparation for inspection tasks. Identifying that the critical path of the project was the intelligent pigging team, I had them arrive on site early in the lead up to the furnace shutdown to mitigate any logistical/connection issues that may arise.

As the furnace was opened – I performed the preliminary inspection with the NDT team and refractory specialist, operating in this manner allowed for initial identification of any serious remedial work scopes that could be undertaken in conjunction with the intelligent pigging operation. Upon undertaking the decoking of the furnace necessary to achieve sufficient cleanliness for the intelligent pigging, it became evident that due to the hardened nature of the scale on the internal surface of the tubes, this task would incur an overrun within the inspection timeframe. The float gained by the NDT activities, which found no necessary repairs, was able to absorb this extension resulting in no detrimental time loss to the overall inspection hourly allowance.

Once the decoking activity completed, the gathering of tube thickness data and metallurgical samples did not encounter issue. Further visual and refractory inspection was able to commence on time and was completed ahead of the allocated time. The summary of the visual report and refractory findings is detailed in **appendix 19.10**. With all inspection activities and the minor refractory repairs completed, the teams were demobilised and the furnace returned to maintenance and operations for reinstatement.

The Gantt chart (figure 16) shows the updated status, reflecting the completed stages:

Planning of Furnace Statutory Inspection

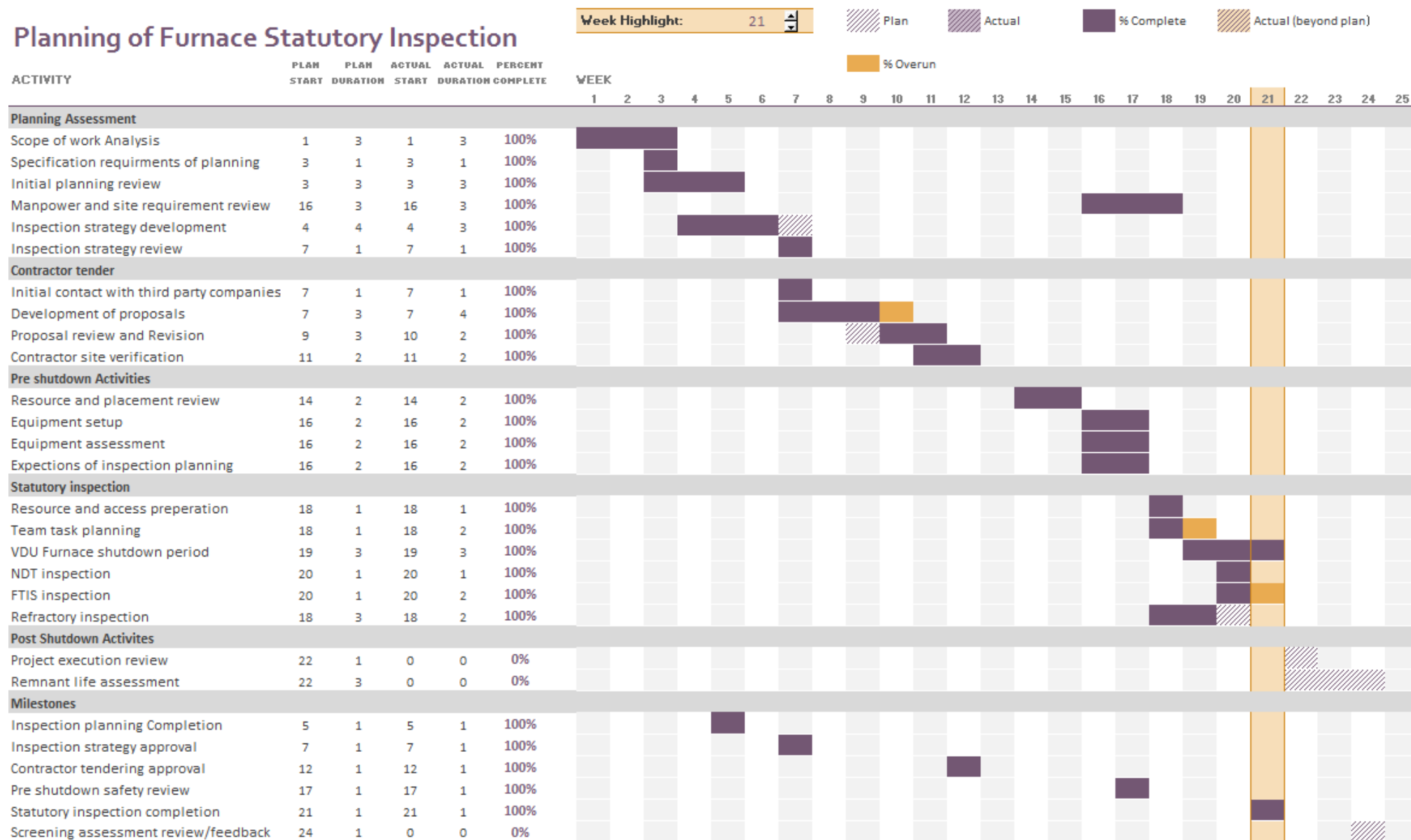


Figure 16: Week 21 updated Gantt chart

13.0 Photographs of work conducted:

13.1 AHAK mobilisation for decoke and inspection activities:



Figure 17: AHAK intelligent pigging vehicles assembling for equipment deployment.

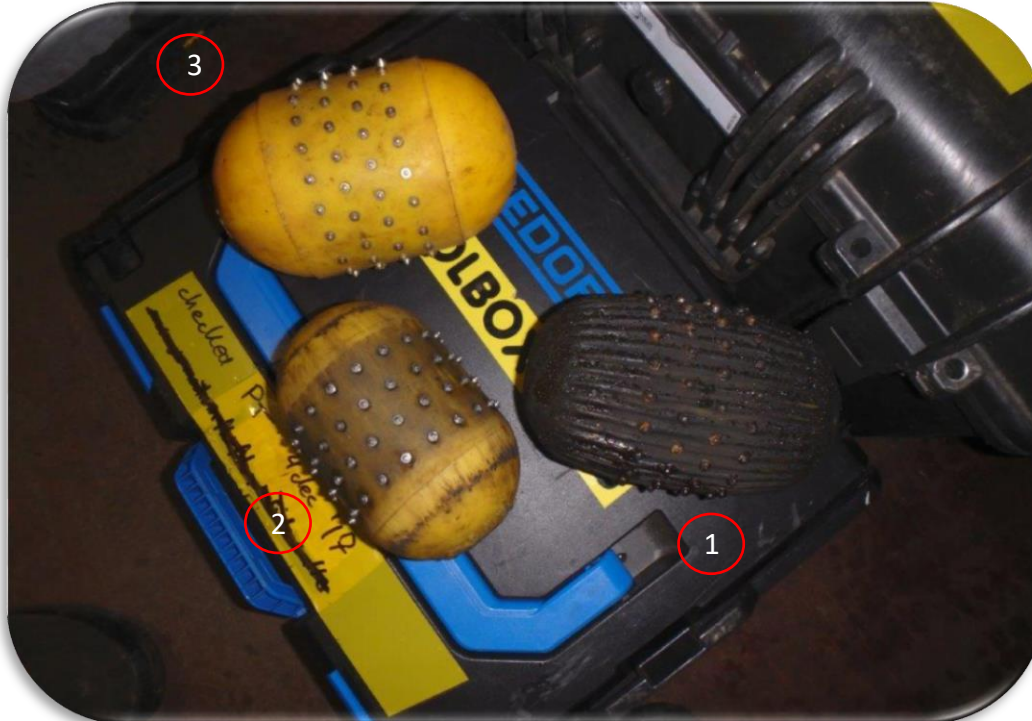


Figure 18: AHAK pigs used for decoking the furnace tubes before USTM data collection.

1- Initial pass, 2- second pass, 3- final pass

13.2 Internal statutory inspection:



Figure 19: *Internal configuration of furnace tubes passes.*

Figure 20: *Levels of scaffolding to allow access wall tubes for damage mechanism assessment.*



Figure 21: *Visual inspection of the roof tubes and radiant sections*

13.3 Refractory assessment and repair:



Figure 22: *Vibration induced refractory damage resulting in localised casing hotspots*



Figure 23: Burner quarl inspection



Figure 24: *Completed refractory repairs to furnace roof*

13.4 Non-destructive testing techniques:



Figure 25: *CAN technician utilising crack detection techniques*

Figure 26: *Metallurgical testing of furnace tube samples.*



Figure 27: *CAN rope access technicians performing inspection of the furnace casing*



14.0 Calculation of remaining tube life

The USTM data gained from the intelligent pigging in conjunction with the process and temperature information collated from database and historical record interrogation, form the basis for the tube remaining life calculation. Industry codes API 579 FFSA (2016) and API 530 (2015) remnant life calculation provided the framework of calculation, the resulting screening assessment focuses on the formulation of the following variables:

- Minimum tube material thickness required for pressure containment (**t_{min}**)
- Tube lifespan corrosion rate (**CR**)
- API 579 (2016) remaining life screening assessment
- API 530 (2015) Estimation of accumulated creep damage using the Larson –Miller parameter.

The final screening assessment for the 4/6/8 inch radiant tube sections was conducted using the refinery computational software 'Vsage', the full analysis and inputs can be found documented in **appendix 19.11**. For documentation and example the process is demonstrated below on the four inch radiant tube section.

14.1 Assumptions of calculation

- Due to no available pressure indicators of the system, the operating pressure of the furnace after discussion with the unit process engineers is assumed at 0.83 Mpa.
- Furnace commission date found in available records is 01/01/1980, and has been applied to radiant tube sections.

14.2 Determination of minimum thickness required for pressure containment.

Industry code ASME B31.3 (2013) permits the use of the Barlow formula to determine the required wall thickness for piping subjected to internal pressure. Muhlbauer (2003) writes of the use of this formula commenting *“Barlow’s Formula is a calculation used to show the relationship between internal pressure, allowable stress (also known as hoop stress), nominal thickness, and diameter. It is helpful in determining the maximum pressure capacity a pipe can safely withstand.”*

The formula expressed:

$$\text{Minimum required thickness} = \frac{P D}{2 S E}$$

Where:

- P = Pressure (Mpa) (0.83Mpa)
- D = Diameter (mm) (4” tubes > 114.3mm)
- S = allowable stress of material (Mpa) (A335 9Cr-1Mo specification = 55.48Mpa)
- E = Longitudinal quality factor (given as 1 for seamless pipe)

Applying the conditions of the four inch radiant tubes achieves:

$$\text{Minimum required thickness} = \frac{0.83 \times 114.3}{2 \times 55.48 \times 1}$$

Therefore a minimum of **0.85mm** thickness required for pressure containment.

Consulting the Valero standard of “commitment to excellence management” (CTEMS) a conservative future corrosion allowance of 1.66mm is added as factor of safety and rounded to a figure of **2.5mm** which will be used for the determination of remaining life calculation.

14.3 Establishment of furnace data set

To conduct further investigation the operating conditions of the furnace from commission, must be established. This is collated through database interrogation of the refinery's unit health monitoring (UHM) system and review of historical documentation. Due to the requirements of API 530 (2015) code calculation a minimum data set of 15 points is necessary. This is achieved through the population of the below **table 3**.

Period	Years	Date range	Average tube wall temperatures (°C)
1	22	1 st Jan 1980 – 31 st Dec 2001	593.48
2	2	1 st Jan 2002 – 31 st Dec 2003	554.00
3	3	1 st Jan 2004 – 31 st Dec 2006	561.06
4	1	1 st Jan 2007 – 31 st Dec 2007	620.00
5	2	1 st Jan 2008 – 31 st Dec 2009	581.11
6	1	1 st Jan 2010 – 31 st Dec 2010	593.48
7	1	1 st Jan 2011 – 31 st Dec 2011	557.48
8	1	1 st Jan 2012 – 31 st Dec 2012	568.94
9	1	1 st Jan 2013 – 31 st Dec 2013	620.00
10	1	1 st Jan 2014 – 31 st Dec 2014	544.26
11	1	1 st Jan 2015 – 31 st Dec 2015	558.54
12	1	1 st Jan 2016 – 31 st Dec 2016	552.66
13	1	1 st Jan 2017 – 31 st Dec 2017	558.54
14	1	1 st Jan 2018 – 31 st Dec 2018	640
15	0.83	1 st Jan 2019 – 14 st Oct 2019	640

Table 3: *Furnace data points and average temperature*

Assumptions of data set:

- No UHM data was available prior to 2002, therefore the highest average measured temperature has been assumed.
- Shutdowns in 2007 and 2013 affected the average data, therefore the safe operating limit temperature of 620°C has been assumed.
- Readings post 2017 have been taken at the current safe operating limit temperature of 640°C.

14.4 Corrosion rate determination

To enable the identification of material loss over operational periods, API 570 (2011) outlines the process of corrosion rate determination, this is expressed in the formula:

$$\text{Corrosion rate (mm/yr)} = \frac{\text{Nominal thickness} - \text{Actual thickness}}{\text{Time (years) between nominal and actual thickness}}$$

Where:

- Nominal thickness = furnace tube commissioning thickness stated as 7.239mm from drawing 01-RD-A-74482 (**Appendix 19.2**)
- Actual thickness = As found by minimum measured thickness from the intelligent pigging inspection AHAK report ISP18041_02 Rev.0

Therefore:

$$\text{Corrosion rate (mm/yr)} = \frac{7.239 - 5.7}{39.83} = 0.03864 \text{ mm per year}$$

Applying the corrosion rate to the data set results in the remaining tube thickness at any given period:

Period	Years	Service	Remaining Tube thickness at end of period (mm to 3d.p)
1	22	22	= 7.239 – (0.03864 x 22) = 6.389
2	2	24	= 7.239 – (0.03864 x 24) = 6.312
3	3	27	= 7.239 – (0.03864 x 27) = 6.196
4	1	28	= 7.239 – (0.03864 x 28) = 6.157
5	2	30	= 7.239 – (0.03864 x 30) = 6.080
6	1	31	= 7.239 – 0.03864 x 31) = 6.041
7	1	32	= 7.239 – (0.03864 x 32) = 6.003
8	1	33	= 7.239 – (0.03864 x 33) = 5.964
9	1	34	= 7.239 – (0.03864 x 34) = 5.925
10	1	35	= 7.239 – (0.03864 x 35) = 5.887
11	1	36	= 7.239 – (0.03864 x 36) = 5.848
12	1	37	= 7.239 – (0.03864 x 37) = 5.809
13	1	38	= 7.239 – (0.03864 x 38) = 5.771
14	1	39	= 7.239 – (0.03864 x 39) = 5.732
15	0.83	39.83	= 7.239 – (0.03864 x 39.83) = 5.700

Table 4: Corrosion rate determination

14.5 API 579 remaining life screening assessment

An initial screening assessment of remaining tube life can be undertaken as per API 579 (2016) consisting of the formula:

$$API\ 579\ remaining\ life\ (yrs) = \frac{(t_{actual} - t_{min})}{Corrosion\ damage\ rate}$$

Where:

- t_{actual} = 5.7mm (As found by minimum measured thickness from the intelligent pigging inspection AHAK report ISP18041_02 Rev.0)
- t_{min} = 2.5mm (minimum required thickness for pressure containment + CTEMS conservative allowance)

Therefore:

$$API\ 579\ remaining\ life\ (yrs) = \frac{(5.7 - 2.5)}{0.03864} = 82.82\ years$$

However due to the furnace conditions operating within the creep range, further fitness for service according to API 530 (2015) must be considered.

14.6 API 530 Estimation of accumulated creep damage using the Larson –Miller parameter.

The estimation of accumulated creep damage as outlined in API 530 (2015) is applied to each period of operation of the furnace life. For the purpose of documentation the process will be applied to one period (**table 5**), however resulting assessment for the full data set of the 15 periods is found in **appendix 19.11**

Period	Years	Operating pressure (Pr)(Mpa)	Tube temperature (°C)	Minimum Thickness (mm)	
				Beginning(t _{initial})	End (t _{end})
3	3	0.83	561.06	6.312	6.196

Table 5: *Summary of conditions for API 530 assessment*

Penny (1995) writes of the Larson- miller parameter (Clm) commenting it is a “*time – temperature parameter developed in the 1950’s in order to extrapolate short term rupture test results to long –term predictions*”

Expressed in the formula:

$$Clm = (Tube\ temperature + 460)(16.76 + \log\ estimated\ rupture\ time) \times 10^{-3}$$

In order to identify the Larson-miller value the average stress thickness (σ_{avg}) and rupture allowable stress (σ_r) must be calculated:

Average stress thickness – Calculated using the formula:

$$\sigma_{avg}\ thickness = \frac{(t_{initial} + t_{end})}{2} = \frac{(6.312 + 6.196)}{2} = 6.254\ mm$$

Average rupture strength – Calculated using the formula:

$$\sigma_r = \frac{1}{2} \left(\frac{(Pr \times diameter)}{\sigma_{avg}} - Pr \right) = \frac{1}{2} \left(\frac{(0.83 \times 114.3)}{6.254} - 0.83 \right) = 7.17\ MPa$$

At 7.17 MPa, using the minimum rupture strength, the Larson – Miller parameter can be identified from the parameter curve (**appendix 19.12**) as 30.2 in SI units

With all the variables known the expression for the Larson – Miller parameter can be solved for estimated rupture time:

$$30.2 = (561.06 + 460)(16.76 + \log \text{estimated rupture time}) \times 10^{-3}$$

$$\therefore 30.2 \times 10^3 = 1021.06 (16.76 + \log \text{estimated rupture time})$$

$$\therefore \frac{30.2 \times 10^3}{1021.06} = (16.76 + \log \text{estimated rupture time})$$

$$\therefore 29.58 - 16.76 = \log \text{estimated rupture time}$$

$$\therefore \log \text{estimated rupture time} = 12.87$$

$$\therefore \text{Estimated rupture time} = e^{12.87} = 388481 \text{ hours}$$

Converting this to years, results in an estimated rupture time of 44.3 years.

Using this process, subsequent calculations are then conducted on the 15 data points of the 4" radiant tube section. The entire process is then repeated on the 6" and 8" radiant tube sections of the furnace (As demonstrated in **appendix 19.11**).

15.0 Analysis of inspection

Collating the outputs calculated from the API 579 (2016) and API 530 (2015) screening assessments as formulated by the refinery Vsage algorithms, the relevant conservative figure is then used to estimate the safe remaining life of section tube thickness. The following results can be summarised:

4 inch radiant tube section - Screening assessment remnant life as found by calculation = 42.9 years from 08th November 2019, say 42 years predicting a retiral date 08th November 2061. The screening remnant life is limited by the minimum allowable thickness given conservatively at 2.5 mm and the future corrosion rate according to API 579 (2016) assessment.

6 inch radiant tube section - Screening assessment remnant life as found by calculation = 94.6 years from 08th November 2019, say 92 years predicting a retiral date of 08th November 2111. This screening remnant life is limited by the remaining creep life according to API 530 (2015).

8 inch radiant tube section - Screening assessment remnant life as found by calculation = 80 years from 08th November 2019, predicting a retiral date of the 08th November 2099. This screening remnant life is limited by the remaining creep life API 530 (2015).

Analysing the quality of input data, it is important to note that due to the possibility of inaccuracies of recorded data and uncertainties surrounding the evidence of specific operating conditions during the 39.83 years of history, that conclusions cannot be drawn solely on the resulting calculations, but rather must be assessed in conjunction with the findings of the additional techniques conducted within the scope of the statutory inspection.

The factor potential for accumulated creep damage, as found to be a limiting factor in both the 6 and 8 inch radiant sections can be largely mitigated by the findings of the metallurgical survey conducted during the internal examination. It was found that whilst the microstructures of the replicas indicate the early stages of spheroidisation which is indicative of high temperature service, no evidence of creep cavitation was detected at any of the locations examined.

With the furnace returned to service, having rectified the minor issues identified through the visual and refractory inspections I would not anticipate further deterioration of structure now that the furnace returns to steady state operation, evidence gained through experience of equipment inspection and the accumulated history of this furnace, demonstrates that failures of this nature occur only due to the process of shutting down/startup and unplanned process disruption. The results gained from the non-destructive testing techniques, which found no identifiable indications within the agreed scope of examination, provides evidence that the pressure envelope integrity of the furnace remains stable.

A discussion with a multi-disciplined team was conducted with the objective of re-evaluating the furnace according to the risk inference matrix as outlined in section 7.0. The outcome of which found that the consequence of furnace failure remains unchanged at a level 3 safety and business loss. The likelihood of an event to occur however, in light of the determination of potential remaining life and satisfactory furnace structural and pressure integrity, can be downgraded to a conservative category B where conditions may allow for an event to occur within industry using similar technology. The overall risk therefore alters from 'level 2 Unacceptable' to a 'tolerable risk' (TR) stature (**table 6** below).

Valero Risk Matrix - Modified for Pembroke.											
Business	Environment	Consequence									
		Community	Safety								
>\$100 Million	Catastrophic - Serious contamination of ground water or water course, extensive loss of aquatic life.	Public Evacuation or National Media Coverage	>10 Fatalities On Site or Multiple Fatalities Off Site	VI	TR	Level 1	Level 2	Level 3	Level 4	Level 4	Level 5
>\$10MM to \$100Million	Major - Serious toxic effect on beneficial or protected species, significant fish kill over a five mile range.	Public Evacuation or Country Media Coverage.	2 to 10 Fatalities On Site or One Fatality Off Site	V	TR	TR	Level 1	Level 2	Level 3	Level 3	Level 4
>\$1MM to \$10MM	Severe - Hazardous material into water course with half mile effect, e.g. Visible Fish kill	Shelter in Place or County Media Coverage	Permanent Disabling Injury (e.g. Amputation) to Single Fatality	IV	BA	TR	TR	Level 1	Level 2	Level 2	Level 3
>\$100K to \$1 MM	Significant - Strong or offensive odours or noise, major breach of permitted emissions	Shelter in Place or Local Area Media Coverage	Serious Injury to Permanent Injury (e.g. Burn)	III	BA	BA	TR	TR	Level 1	Level 1	Level 2
>\$10K to \$100K	Noticeable - Nuisance off site, discernible odours, minor breach of permit conditions	Community Warning or Local Media Coverage	Recordable to Lost Time	II	BA	BA	BA	BA	TR	TR	Level 1
<\$10K	Minor - Nuisance On site only, No off site effects	No to minor impact to people or No Media Coverage.	Minor to First Aid	I	BA	BA	BA	BA	BA	BA	TR
Likelihood					AAA	AA	A	B	C	D	E
Qualitative description					Rare - equivalent to being killed by a lightning strike.	Remote, has occurred once or twice in the Industry	Unlikely that the event will occur at this facility.	Conditions may allow the event to occur within industry using similar technology	Conditions may allow the event to occur at this facility during its lifetime	Likely to occur at this facility once every 10 years	likely to occur
Scenario frequency per annum					10-7 to 10-6	10-6 to 10-5	10-5 to 10-4	10-4 to 10-3	10-3 to 10-2	10-2 to 10-1	10-1 to 1

Table 6: Updated Valero Risk inference matrix (Valero, 2017)

16.0 Recommendations resulting from statutory inspection.

With the statutory inspection and analysis of data complete, approval of the final report and subsequent alteration to the written scheme of examination was actioned with the following recommendations:

- Due to the extensive historical data for this furnace and absence of significant inspection, reliability and integrity issues, the interval of this furnace will be increased to 36 months from 24.
- Subsequent inspections undertaken in addition to the normal work scopes of internal examination and NDT, shall include the special emphasis techniques of intelligent pigging and metallurgical examination, to allow for the establishment of a targeted corrosion trend and to test for the presence or extent of creep cavitation.
- As further data points at subsequent inspections are gained, and confidence in the techniques and the data yielded is established, If no significant increase in corrosion rate and material loss is evident; the conservative minimum thickness figure of 2.5 mm can be reviewed for refinement towards the required value for pressure containment, with the objective of extending the interval between internal examinations.
- Future skin temperatures should continue to be controlled and monitored to the same standard as currently, or improved. If changes to both process and temperature occur deviating from the current operating conditions, re-assessment of potential remaining tube life must be undertaken before altering the pressure envelope of the furnace.

17.0 Conclusion

The future potential savings that employing an RBI approach to furnace inspection is difficult to define until a successful subsequent inspection regime is established and found favorable. It has been demonstrated however, that a preliminary extension to the written scheme of examination to 36 months is justified by dynamic risk assessment, benefiting the refinery financially as highlighted within the costing justification of section 9.6. Looking towards future intervals, and judgments based on the outputs of inspection data and tube remnant life screening assessments, it is the objective of risk based inspection practices to extend the interval further to 60 months. This has approach if adopted as standard practice across all 15 furnaces on the refinery, has the potential for significant business savings without compromising the longevity and reliability of the equipment.

When considering the value gained from the furnace engineering review the aims and objectives of section 8.0 can be evaluated:

“To create a written scheme of examination for the refinery heater and to develop an inspection test plan strategy to satisfy the data gathering, necessary for risk based analysis.”

Through dedicating adequate resource and time to the historical review of the furnace in the preliminary stages of the project, I was able to hone and identify the relevant techniques required for a successful testing plan. My focus and development of the previous written scheme of examination provided a base document from which to incorporate the new approach of risk based inspection. Importantly collaboration with the other discipline engineers such as the process department and our resident corrosion subject matter expert,

provided a means of independent review of the proposed strategy, to ensure it was adequately structured before submitting it for authorization to the Chief Engineer.

Setting the clear expectations of extent and quality of data in this manner, I was able to coordinate my NDT team and the specialist contractors under my supervision to successfully gather the information required to complete the subsequent screening assessments.

“To successfully coordinate, plan and execute the internal inspection of a refinery heater on the vacuum distillation unit.”

Employing dynamic and efficient management and oversight techniques such as daily meetings, contractor briefings and mid and post task analysis between myself and my team, I have been able to plan and execute the successful internal examination of the furnace. The individual actions of the differing sub-contracting tasks had to take place concurrently during the outage, and were on times often time critical to the overall outage schedule. During the execution of these tasks my focus on team communication proved effective in mitigating issues that arose, allowing for prompt action to be taken. Examples of this included directing additional support, resource and the identification and approval of fault rectification. Furthermore I gave focus to having a prominent onsite presence while the inspections of the furnace were in action, giving me valuable information to the progression of the varying work scopes and up to date developments of where further efficiencies and emphasis could be made.

“To analyse the resulting data using a combination of industry approved API codes and a sound engineering approach, providing justification for reassessment against the Valero risk assessment matrix.”

To adequately perform the resulting screening assessments for tube remaining life, significant consideration was given to the identification of industry standards and legal legislation in order to implement recommendations. By improvement of my knowledge and understanding of the PSSR regulations and how the industry codes of API 571, 579 and 530 can be applied to quantitative data, I have been able to present an alternative inspection strategy to deliver significant business savings. Through assessment of the furnace via the refinery risk inference matrix, key elements of damage mechanisms and their contribution to furnace failures became apparent. Assessing exactly how the mechanisms evolve within the pressure envelope of the furnace allowed for NDT techniques to effectively identify their presence and document their extent. The advantages of the information gained through this targeted approach meant that time during the internal inspection was used to the best of its opportunity. Evidence of this is demonstrated through the reports and results of the intelligent pigging and refractory analysis, the recommendations from which then formed the foundations for tube remnant life calculation as per the industry approved codes. The resulting reassessment according to the Valero risk matrix allowed for the conclusion of the new grading of 'tolerable risk' to be found (section 15.0).

“To formulate recommendations from technical analysis, to better guide the owner-user to plan examinations based on consequence and likelihood of potential mechanisms.”

Through thorough analysis of the inspection findings I have presented recommendations as to the ongoing strategy of the refinery furnace (section 16.0), as subsequent internal examinations are completed, confidence in the techniques and data will reinforce the corrosion history and justification for the continued use of the RBI approach.

To summarise, the management and execution of the overall internal inspection was completed in an effective manner without significant business interruption or safety loss. The resulting outcome has been that future internal examinations can now be actioned at greater intervals than previous operating runs, allowing the business greater flexibility when considering planned outages and allocation of resource.

Figure 28 below shows the completed Gantt chart demonstrating the successful implementation of each planning execution and analysis stage, actioned within its allocated timeframe. The Gantt chart also reflects the challenges presented in the preliminary stages the most prominent of which was the logistical issue of having a sub-contracting company based in the Netherlands attend site for the intelligent pigging operation. This challenge however was managed effectively resulting in the timely completion of all necessary paperwork and approvals, resulting in no detrimental effect to subsequent and concurrent tasks. Undertaking the lead role for this outage has presented me with a range of invaluable experiences and enhancement of technical knowledge that I will look to continually develop through my role as engineer as well as skills that I will incorporate into the future projects as the refinery enters a new period of turnaround maintenance activities.

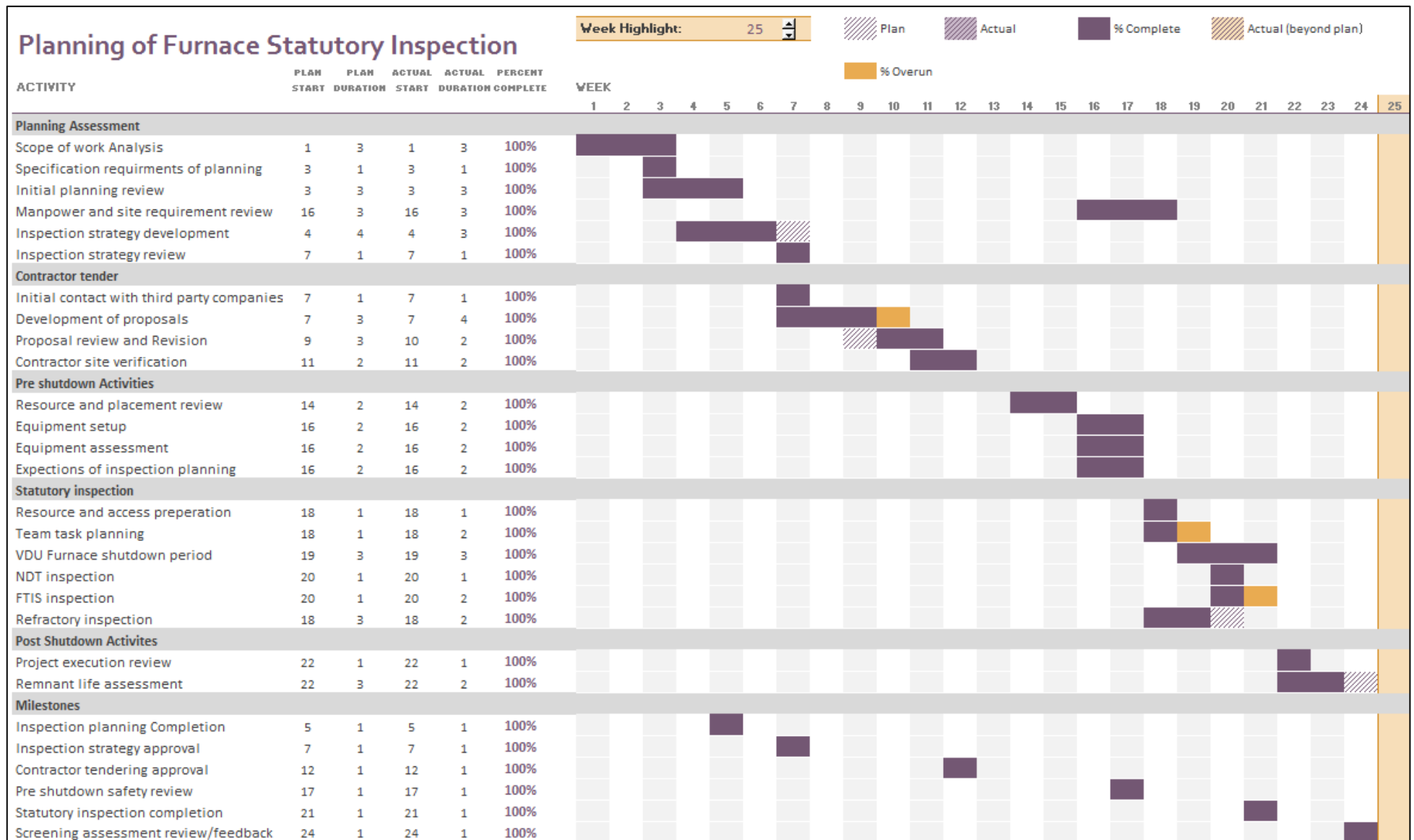


Figure 28: Completed Gantt chart

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