AN APPROACH TO POWER STATION BOILER AND TURBINE LIFE MANAGEMENT

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Abstract: The de-regulated electricity market which has existed in the U.K. for around 15 years has led to energy companies operating their power plant flexibly to maintain profitability in a very competitive commercial environment. To do this, the company maintains a very strong engineering capability in the area of structural integrity of boiler components and high temperature rotating plant.

The key issues for the older 500 MW boiler plant which is daily two-shifted and operates at temperatures well into the creep range for low alloy steels are fatigue and creep damage, the latter which is influenced greatly by the operating hours seen by the older coal-fired units which have exceeded their design lives. Major components of the boiler which are subject to rigorous and thorough examination are headers, drums and high energy steam pipework. Methodologies include on-line plant damage analysis for controlling degradation and optimising start-up procedures, plant modifications, innovative repair and retro-fitting with improved materials.

Steam and gas turbine rotors operate at high speeds at elevated temperatures. Maintaining rotors in a good commercial and safe operational condition in compliance with any regulatory requirements can also bring increased efficiency and reduced costs, for example by incorporating proactive measures into planned overhauls.

We have developed procedures for both prevention of creep cavitation cracking and assessment of bore high strain fatigue life (for hollow rotors). These use material data, temperature and stress information along with the results of NDE inspections to determine any operational constraints (starts, temperatures, and running hours) which may be necessary. Vibration, which can be an indication of cracking in an operating rotor is monitored remotely and on-line.

Introduction: UK electricity producers operate within a very competitive market requiring much of the older 500MW coal-fired plant to operate flexibly, subjecting it to numerous start-up and shut-down and load following cycles. With optimised procedures and advanced controls and instrumentation, start-up on a hot unit, from fans in service to synchronisation can be reliably achieved within 60 minutes. However, power plant components are exposed to increased levels of fatigue loading that can lead to significant damage. The cost of two-shifting damage has to be accounted for within the trading equation and therefore plant owners and operators want to understand:-

- The risk of damage and breakdown failure on their particular plant.
- How to safely manage the risks.
- Risk variation with flexibility parameters, eg. shorter/longer start time, faster/slower loading rates.
- The extent and cost of inspection and component replacement programmes and how they can be optimally organised.

Since boiler pressure parts can account for a significant proportion of unplanned availability losses and are often limiting factors on plant flexibility, knowledge of component life in relation to future plant utilisation is required to achieve optimum performance. The management of integrity of boiler tubes, elements and headers is an essential element of this strategy. Header failure in particular would be a serious safety concern as well as forcing long and expensive outages. They are however more predictable than tube failures and can be prevented through careful planning of inspection, assessment and refurbishment programmes. For steam turbine plant, "flexible operating" capability is primarily defined by the following parameters:

- Maximum number of start up / shut down cycles without incurring unacceptable material degradation.
- Minimum time from barring speed to full MW load for a range of initial HP and IP casing temperatures.
- Maximum rates at which MW load can be increased and reduced.

This paper reviews a number of technical issues that have arisen on UK power plants within the competitive market that will be of interest to owners and operators in other newly developing markets. The creep life of major components such as steam headers, pipework and turbine rotors may already be a concern on older plants as they have generally surpassed original design life by a large margin. In the UK older plants were nominally designed on the basis of 100,000 hours and a number now approach 200,000 hours of operation.

Boilers.

Fatigue in Superheater Headers: Internal ligament cracking has become a common form of thermal fatigue and creep/fatigue damage affecting superheater headers (Fig. 1). Cracking can propagate through wall rapidly with adverse stub geometry and if operating techniques are not optimised (eg. 230 starts), though headers can be safely operated with quite severe cracking provided a leak-before-break case can be made. RWE Innogy has applied specialist instrumentation and developed damage analyser software and control room desk displays to advantage:

- Refining start-up and shut down techniques to avoid or reduce damaging events
- Managing severely cracked headers safely through further operations to a commercially acceptable time for replacement outage (Fig. 2).
- Monitoring crack initiation and growth to underwrite prolonged intervals between inspection.
- Rating design changes for replacement headers.
- Predicting crack initiation and crack growth in new headers.

Inspection identifies the worst cracked zones in headers and special thermocouples have been used to give on-line stress displays to the operator. Though unsophisticated, temperature ramp limits and simple fatigue stress limits have provided a first line operational defence for operators. They have also facilitated the measured introduction of less damaging procedures such as back venting and progressive drainage, balancing gland steam and drainage and boiler leading turbine. Advanced creep/fatigue crack growth models are more computing intensive and have been used to underwrite safety when it has become necessary to operate headers at an advanced stage of deterioration. Figure 2 shows the Damage Analyser output being used to limit crack growth to less than 3mm (0.12ins) in a final superheater outlet header where cracking approached 70% through wall.

By modifying start-up and shutdown techniques (whist maintaining commercial flexibility) the lives of headers have been at least doubled. For example a cracked 100mm (4ins) thick 2Cr superheater outlet header was replaced after 600 starts in an identical design which was then operated for 1,200 starts under modified procedures. On a different boiler utilising a revised stub layout, the replacement, still in thick section 2Cr, lasted approximately 1,800 starts. Replacement with 9Cr in half the original thickness with modified stub layout has given far longer lives (greater than 5,000 starts predicted).

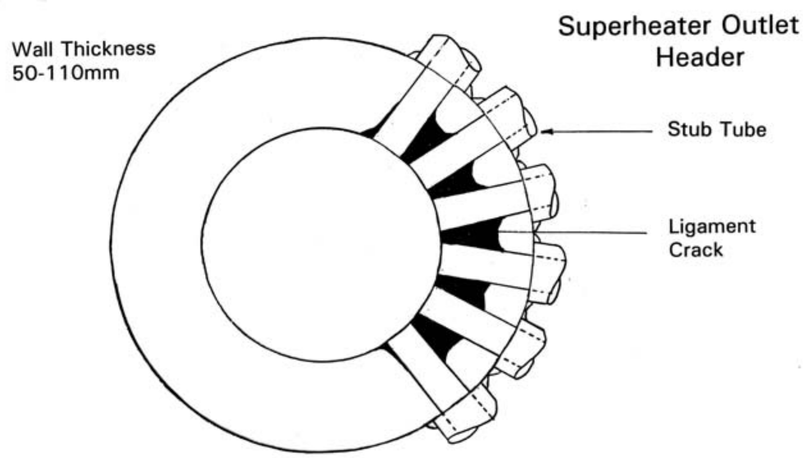

Figure 1
Ligament Cracking in Superheater Header

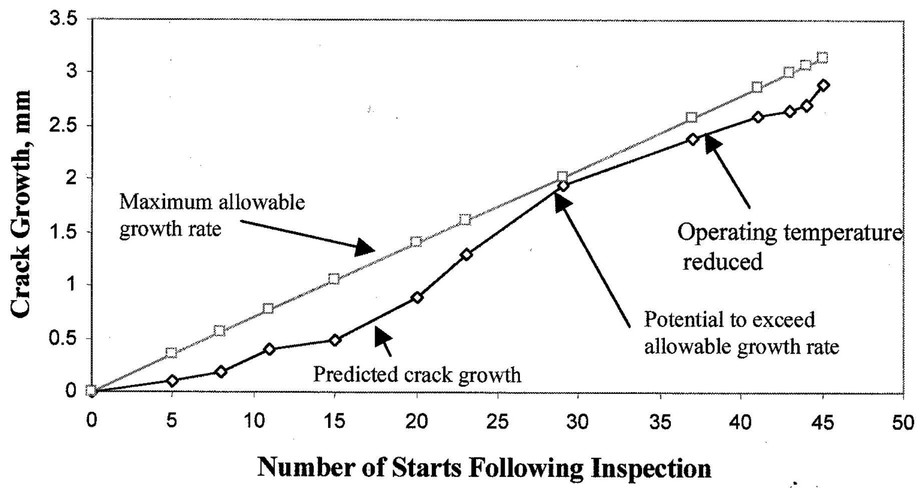

Figure 2
Managing Crack Growth in a Severely Cracked Header

Creep in Superheater and Reheater Headers: With extended life of older plant, creep continues to accumulate in superheater and reheater headers and appropriate management of integrity has to be applied to prevent rupture. RWE Innogy adopts a three stage approach that is designed to single out components for which there is a risk of failure by creep rupture during the life of the plant. The stages of assessment require more refined life estimates or more inspections to be made as the component approaches the end of its assessed life. In this way, effort is concentrated on the components of major concern and costly replacement is avoided. We have been able to safely and cost effectively extend header life using creep logging software with thermocouples attached to headers and stubs (RWE Innogy Creep Life Package). Paper-based and analytical computing assessments however only go so far and to gain further economic advantage, expertise in physical measurements, sample testing, NDE and metallurgical assessments has been developed and applied. Though a burden during outages, such inspection based assessments are very cost effective and have deferred investment on replacement headers for many years.

Damage to Superheater and Reheater Elements: Flexible operation often leads to tube temperatures transiently peaking above normal, these arise typically prior to synchronisation in radiant and platen surfaces and post-synchronisation in pendants. We have identified a number of problems associated with high peaking metal temperatures from which tube failure risk increases, for example:-

- Element distortion, itself leading to a higher degree of local overheating, long term overheating or fireside corrosion failures.
- Occasional short-term overheating failures.
- Degradation in tube material properties leading to lower tolerance of transients.
- Disruption of protective oxide leading to enhanced metal loss rates (unlikely unless temperatures peak above 650C).
- Degradation of transition joint integrity.
- Fatigue at slip ties leading to crack formation in tube walls and tube misalignment, seal boxes and header stubs due to differential expansion.

Special packages of thermocouples were fitted throughout steam circuits on selected boilers to assess these risks. The results were used to optimise operating techniques as far as possible though it was not always economic to avoid all degradation risks. In these cases targeted inspections at outages have evaluated failure risks and refurbishment implemented or modifications devised. Experience has also aided the siting of a minimum number of gas side thermocouples as these are both costly to fit and to maintain. Operators require peak temperature limits to work to and RWE Innogy has moved away from traditional limits based on longer term creep to transient temperature limits which provide for more commercial operation. A package of enhanced thermocoupling (the commercial package) is usually required to remain on the plant to successfully operate a boiler in a flexible mode whilst controlling damage or risk of tube failure in areas identified as vulnerable.

As discussed above, in order to achieve a commercially acceptable tube failure risk has required investment in modifications, for example, partial replacement in stronger materials, re-siting of material transitions, redesign and re-siting of supports, ties, wrappers and alignment straps.

Steam Pipe Weld Bore Cracking: Recently in the UK a new form of damage has been found in headers and main steam pipes. It takes the form of internal cracks initiated at the bores of headers and pipes at weld bead penetrations (and changes of section) which have propagated into the pipe wall (Fig. 3).

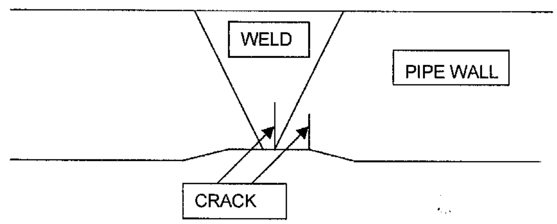

Figure 3
Location of Bore Cracking in Main Steam Pipes

The cracks generally extend fully circumferentially around the bore of the pipes with depths typically in the range 5-20mm in 65mm wall, though deeper cracks have been found. The cracks are effectively transparent to standard ultrasonic methods of inspection as they are narrow, oxide filled and have straight smooth sides. Because of this and their position, bore cracks have remained undetected for some time. The cracks are due to thermal-fatigue caused by start-up and shutdown though they may continue to propagate on-load. Assessment methodology and safety cases have been prepared to underwrite continued operation, in the main without widespread repair at the present time. These take account of co-existing creep damage measured in the heat affected zone of the welds. We have now developed specialist plant models to assess crack propagation rates and assist with plant operational changes and temperature control systems to minimise further growth (and avoid initiation in uncracked welds). Specialist NDE using the time of flight diffraction method has been developed to most accurately size the cracks.
To date, inspection has revealed bore cracking in the headers and main steam pipes of about half of our older boiler plant.

Turbine Rotors: Steam turbine rotors are among the most critical and highly stressed components in modern power plants. The potential consequences of a rotor failure include blade loss due to disc head failure, spindle fracture from a thermally initiated circumferential crack and most significantly, fast fracture from a near bore defect causing a catastrophic burst. There have been only a few instances world-wide of catastrophic bursts of rotors, but the consequences are invariably severe as the fragmented shaft is unlikely to be contained within the casing. Fragments of up to 450 kg from the failed Gallatin IP/LP rotor which burst in 1974 (Figs 4 & 5), pierced the stations' concrete roof (Schemerling et al, 1976), whilst large fragments of the 71 tonne Irshing LP2 rotor which burst in 1987, were thrown 1300m from the station (Carlton et al, 1988).

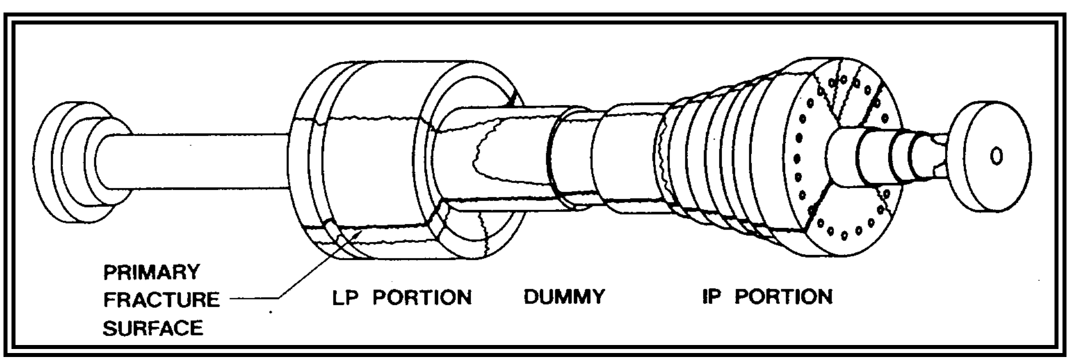

Figure 4 - Gallatin Unit 2 IP/LP Rotor Fragmentation

The risk of injury to personnel from flying debris and escaping high pressure steam is therefore significant.

Manufacturers and electric power utilities quantify and limit the risk of such failures using the concept of "rotor life" which is the maximum number of service hours and / or hot and cold starts that the rotor can be safely subjected to.

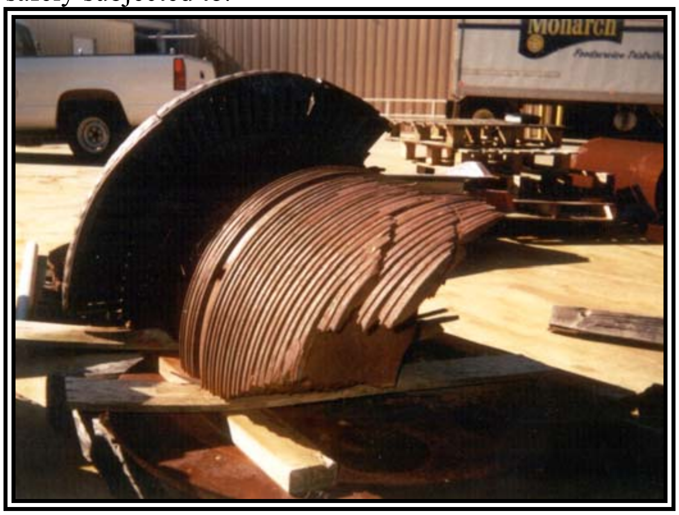

Figure 5 - Gallatin Unit 2 IP/LP Rotor Fragmentation

Reducing start-up times to improve flexibility raises transient thermal stress levels at the rotor bore and surface, whilst the increase in annual start cycles substantially enhances rotor material degradation rate.

Thermal Fatigue/Brittle Fracture

Rotor Bore: Critical defect size is determined by maximum total bore stress and bore temperature during the early part of a cold start when the material fracture toughness is relatively low. When thermal stresses are included, total bore stress is typically highest in the first or second stage disc, which is therefore the critical area. Rotor bore T.F. life is expressed in terms of the number of hot and cold start cycles required to propagate a defect in the near bore region from the initial assumed size (a0) to the critical or final size (ac). The additional ‘secondary’ effect of creep crack propagation (CCP) at steady load, is summated with cyclic damage to give total ‘service invoked’ bore crack depth. Analysis for a 500 MW IP rotor in ‘two shift’ service (16 hrs per start), assuming upper bound CCP rate, shows a bore fatigue life of 1380 ECS if CCP is allowed for and 1150 ECS allowing for fatigue damage only (where ECS = cold starts + (hot starts /4)). Assumption of mean CCP rate would render CCP effect negligible (Carlton, 2002).

Rotor Surface: Rotor surface T.F. damage describes the initiation and propagation of cracks at the rotor surface by low cycle high strain fatigue, due to cyclic thermal stressing under conditions of starting and load changing. Since start up and loading rates are constrained by these transient thermal stresses, effective optimisation of plant life / commercial performance requires assessment of the maximum temperature ramp rates that can be incurred without invoking excessive T.F. damage within planned life. Steam to metal temperature differentials are therefore monitored and controlled during start-up and shutdown to restrict surface stresses to values which will not cause excessive compressive and tensile yielding, thereby limiting the plastic strain range during each cycle to acceptable values.

Rotor surface thermal stresses are greatest in areas of high stress concentration and bore to periphery temperature differential. The most arduous combination of these is found at notches such as the heat relieve grooves of the glands at the inlet end of the rotor, fillet radii at the base of discs, balance holes in discs and blade grooving in reaction type rotors. Figure 6 refers.

The life management policy addresses the risk of shaft fracture due to a circumferential crack originating at the periphery, and progressing by T.F. to a size large enough to allow failure by mechanical high cycle fatigue (due to rotor 'self weight' cyclic bending stresses).

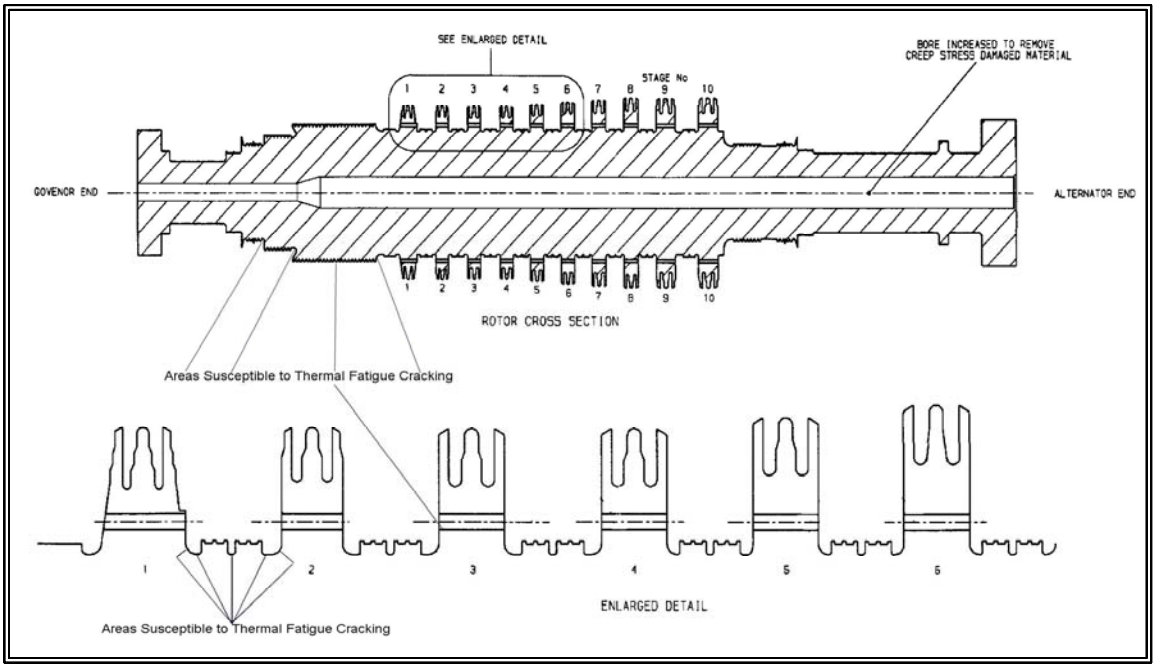

Figure 6 - Thermal Fatigue - Critical Locations

Creep: The RWE Innogy methodology for the assessment of high temperature rotors addresses the potential for rotor bursting due to fast fracture from a crack at the bore surface, or other critical area which originated by creep cavitation and intergranular cracking due to strain exhaustion. A four stage assessment approach is used, with each stage of assessment requiring more refined life estimates or more inspections to be made as the component approaches the end of its assessed life. The locations of areas subject to the highest levels of steady state stress and temperature are illustrated in Figure 7.

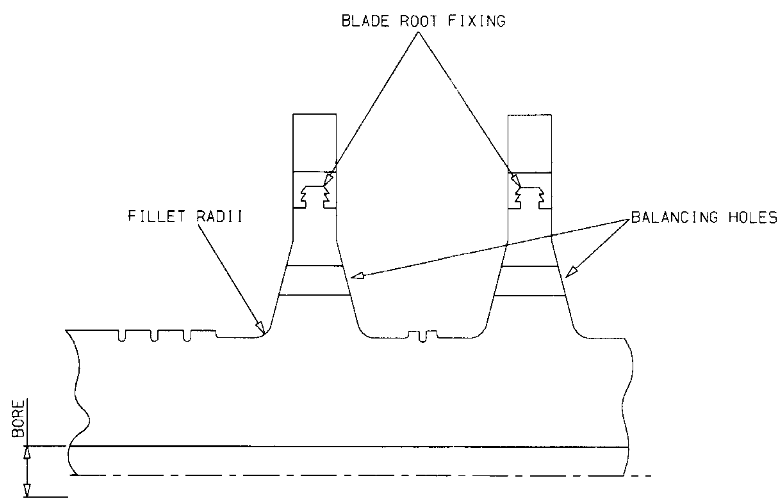

Figure 7 Location of critical areas for accumulation of creep strain

The consequences of fast fracture from a bore defect are extremely severe and maximum allowable creep strain is therefore conservatively limited. Creep rupture at the fillet radii or balance holes could lead to separation of the disc from the rotor body by circumferential cracking, whilst failure at the blade root area would entail loss of blading. Although severe internal damage would ensue, including to adjacent solidly coupled rotors, these failure mechanisms are unlikely to cause casing breach and the consequences are far less serious than rotor bursting. Greater levels of accumulated creep strain are therefore permitted in these areas.

Non destructive examination methods are used to detect and size inherent or service induced surface and sub-surface flaws/defects. These include enhanced visual inspections, magnetic particle, ultrasonic bore inspections and metallurgical assessments. The results are used to confirm theoretical estimates of the location of critical areas for creep and thermal fatigue damage at the bore and surface. Once sized, sub surface defects in the near bore region and defects at outer surfaces are incorporated into revised thermal fatigue life assessments and life extension activities which include machining of the rotor bore to remove strain damaged material and reprofiling of damaged areas on the rotor surface to remove T.F. cracking and reduce stress concentration features.

Regulatory Framework: Within the UK, the Pressure Systems Safety Regulations 2000 govern the in-service inspection of boiler plant. RWE Innogy has extended operational periods between major outages with justifications based on a technical review of each pressure system. This is done prior to each major outage (major outages are typically every 4-6 years) and formally reports the assessments of damage, both creep and fatigue, accumulated in major components and compares the remaining life with the predicted operating hours and cycles between outages. Inspections to underwrite the assessments are identified and reported within 28 days of the return to service. These formal reports also provide the basis of a plant status database.

RWE Innogy maintains a suite of Technical Procedures written by its own plant experts which are used to assess and manage risk on power plant. These consider the risk issues from an operator's perspective combining safety, operational and commercial factors. Creep and fatigue on boilers, pipework, turbines and auxiliary plant are covered. We have in excess of a hundred procedures covering all aspects of power plant.

Optimising Inspection and Replacement Programmes: The process followed involves the forward projection of a range of operating regimes characterised in terms of maximum and minimum utilisation, converted into running hours and types of start-up cycles. These parameters influence the most common failure mechanisms that determine the service life of boiler and turbine components, namely creep and fatigue. Necessary work can then be defined based on assessment of remanent life at various points in the forward projection. Site work consists of periodic inspections and replacements, either partial or complete, to enable safe continued operation. Finally the timing of replacements can be examined and optimised taking account of statutory outage programmes. With design, procurement and fabrication lead times of up to six months, this work requires detailed forward planning.

Unit Controls: In association to the plant modifications, inspections and improvements carried out, Unit controls have also been re-appraised resulting in integrated control platforms being fitted to some units. These platforms have not just transferred the basic infrastructure across but have included logic based controls to enable the units to be automatically controlled in certain of the starting and other functions - the Start-up Management System. This has been utilised in the main for the activities of sequence event planning and the unit progressive drains management. The drains management is where the temperature and pressure parameters of the major components are automatically controlled to pre-set values, this results in a consistent start-up every time, reduces damage and affords the operator time to oversee the start with more information to hand.

Balancing the Commercial Equation: Simplistically, when damage and accumulation rates have been minimised on the plant and the costs and timing of refurbishment identified, the actual damage cost per start can be evaluated. This is added to other flexible operation costs (eg.

start-up fuel costs, manning levels, integrated controls, other plant refurbishment cost) and valued against the market returns captured through operating flexibly. Sensitivity studies determine how the costs can be influenced by adopting different levels of flexibility, eg, times to synchronisation, loading rates, etc. In reality the balance is far more complex as other factors such as investment constraints and environmental limits, may affect operating flexibility also. A comprehensive business analysis has to be carried out to refine the costs.

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