Unscheduled failures of primary reformer catalyst tubes are one of the most common and costly causes of syngas plant shutdowns. A single tube failure may result in an outage costing many millions of dollars in asset repairs and loss of production. The risk of online failure can be significantly reduced by effective inspection and life assessment. Quest Integrity pioneered the measurement of creep strain using their proprietary inspection techniques to follow the progress of creep damage in catalyst tubes. These inspection tools have been supplemented by specialised life assessment methodologies, and have resulted in a deeper understanding of damage accumulation and the confident development of tube...
replacement strategies. Given the trend to longer run times, a particularly significant advantage has been the identification of tubes in danger of failure before the next scheduled outage. These methods have been applied for many years and there are a growing number of examples for which it is clear that online failures have been avoided. This includes:

- Tubes predicted to fail and left in the furnace subsequently failed. This has occurred on a number of occasions.
- Onsite life assessment at the time of the inspection predicted that a tube was close to failure, requiring immediate replacement.
- A life assessment based on a previous inspection indicated a number of heavily damaged tubes. The next inspection confirmed this finding, revealing a number of tubes were unlikely to survive to the next outage.

This article describes the capabilities of highly developed inspection tools, specialised life assessments and their application. This is illustrated using case studies of inspection and life assessment that have successfully identified damaged tubes, which either lead to online failure or would not have survived until the following scheduled outage.

**Plant reliability**

The importance of plant reliability cannot be overstated. A typical steam reformer catalyst tube failure will likely involve a plant outage of the order of one week or more, and the cost associated with such an outage is measurable in millions of dollars. Steam reformer tubes suffer progressive damage due to creep. Understanding the rate and extent of creep damage is an essential input to reliable operation. Inspection of catalyst tubes is an essential aspect of any asset integrity management programme.

Inspection of steam reformer tubes is problematic using traditional inspection methodologies:

- Ultrasonic inspection is difficult due to the high attenuation typical of the spun cast, coarse grained alloys universally used for catalyst tubes. Ultrasonic techniques require a couplant and have required flooding of the tubes during inspection.
- Radiographic inspection is not a feasible technique due to the large areas to be inspected and the significant health and safety requirements.
- Eddy current signals are affected by a large number of factors and interpretation is difficult. Nonetheless, significant experience using eddy current as a base technology has been established and success using this technique has been achieved.

All of these techniques, certainly in their generic form, primarily target cracking and flaw detection. Creep, however, is a deformation process and cracking may not occur until late in life. Figure 1 is a schematic illustration of a creep curve, indicating at which part of the life process the various inspection technologies will generate meaningful data. As a deformation process, the progress of creep involves the development of strain. In the case of internally pressurised tubes, the consequence of creep is an increase in diameter. Some specially developed inspection tool technologies, including Quest Integrity’s LOTIS® and MANTIS technologies, are now well established and have one fundamental objective: the measurement of tube diameter. This increase in diameter is a creep strain and is a direct and simple measure of the progress of creep damage. The data obtained from such an inspection not only provides qualitative information about the extent of creep damage but is also directly amenable to input to life assessment procedures.
Quest Integrity also developed a methodology and software package for that purpose, known as LifeQuest Reformer™. This has involved:

- The development of a comprehensive database of reformer tube alloy creep properties to understand and quantify the change in creep strength through the life of a tube and define the creep history in terms of strain development.
- Performing comprehensive finite element modelling of the tube to account for changing stress distributions at startup and shutdown and during steady state operation.
- The application of a well-established creep model to generate remaining life information from the inspection data, creep property database and calculated stress distribution.
- Using the results of the output from this model to generate comprehensive information and recommendations about tube replacement, tube procurement, and furnace process operation and temperature control.

This customised software life assessment application is consistent with the requirements of API 579 Level 3 fitness for service assessment.

The combination of inspection and specialised life assessment has led to a growing body of experience. This article briefly describes the technologies behind these techniques and describes case studies in which their application has prevented online failure or, as in one case, predicted failure that subsequently did occur. The primary objective of the specialised assessment software is remaining life. In addition, however, a wealth of diagnostic information is developed.

Quest Integrity’s advanced inspection technology, LOTIS, has been deployed for approximately 20 years and has undergone a number of upgrades to improve accuracy and precision. This spinning laser-based tool accurately maps the internal surface of a tube as it passes from top to bottom. This requires the tube to be free of catalyst. The opportunities for advanced inspection have fallen significantly over its lifetime as the average run time between catalyst replacements has increased. This led to the development of an external crawler known as MANTIS (Figure 3), which has the same primary objective as LOTIS, i.e. the measurement of tube diameter and strain. The combination of LOTIS and MANTIS allow inspection at all convenient outages. Both systems generate similar comprehensive information. Figure 4 shows an example of a profile for a single tube and Figure 5 shows tube data over an entire furnace allowing the identification of local hotspots. The dataset used in the creation of these graphical representations of strain can be analysed as required and formatted for input to the specialised life assessment package.

**Life assessment technology**

The specialised life assessment technology, known as LifeQuest, life assessment flow sheet is illustrated in Figure 6.

![Figure 3. External crawler tool technology.](image)

![Figure 4. Tube profile data.](image)
Conventional life assessment, such as the Larson Miller approach\textsuperscript{1}, requires knowledge of:

**Material properties**
Creep strength of most materials is well represented by standard data.\textsuperscript{1,2} Reformer tube materials, however, are subject to in-service ageing, which means the creep strength continuously changes relative to the as-cast strength provided by tube manufacturers. The creep properties and the changes that occur due to temperature and time have been extensively studied and a comprehensive database developed.\textsuperscript{3}

**Stress**
The hoop stress is known accurately from operating pressure. LifeQuest enhances the stress information by finite element analysis to account for through-wall temperature gradients and startup/shutdown cycles.

**Temperature**
Creep life is strongly dependent on temperature. This is an input around which a large degree of uncertainty exists. Measurement of tube metal temperatures in reformer furnaces is problematic with potentially large errors. Typical measurement uncertainty of the order of 30$^\circ$C will introduce errors in remaining life calculations from -75$\%$ to +300$\%$.\textsuperscript{4} The LifeQuest reformer does not require input of temperature data. The strain-based creep property database allows the process to be reversed by calculating the temperature at which the tube had operated in order to generate the amount of strain measured at the time of inspection.

The LifeQuest model takes the inspection data, the creep model database and service process information to calculate the progress of strain into the future. The model is similar to the Omega approach which has found wide acceptance as a life assessment methodology.\textsuperscript{1} The essential output from the model is:

- Predicted failure date.
- Recommended replacement date.
- Calculated tube skin temperature profile.

This information leads to:

- Significant reduction in the risk of unscheduled online outages.
- Targeted tube replacement planning.
- Justification for tube procurement.
- Balancing of furnace process output against tube life consumption.

These inspection and life assessment methodologies combine to represent a powerful tool in providing the important information required to ensure the reliable operation of reformer furnaces. In the following section, a number of
case studies are presented. These case studies show the flexibility and problem solving capabilities.

**Case study: recovery from overheating incident**

An ammonia producer operating a furnace containing 72 HP50Nb modified reformer tubes suffered an overheating incident in which seven tubes were ruptured. Additional damage occurred to the outlet manifold bull tees and there was significant refractory damage. Quest Integrity was invited to assist with the investigation into, and recovery from, this incident. The damaged tubes were identified and replaced. A significant question was the extent of damage to the intact tubes and whether or not these tubes would survive to the next scheduled outage. The LifeQuest reformer assessment methodology was employed to define a ‘critical strain’, above which the risk of failure before the scheduled outage was considered unacceptable. This investigation took into account both the strain that had occurred previously and the short-term strain that had occurred during the overheating incident. The ongoing commitment to inspection by this operator meant that the data differentiating between progressive in-service creep strain and short-term strain was available for analysis.

This analysis identified 14 tubes to be changed within one year and a further 22 tubes to be replaced at the following shutdown in 2016. Unfortunately, the furnace suffered a tube failure in 2014, implying that the life assessment – in the case of one tube at least – had been incorrect. On investigation however, it was found that the tube that failed was one of the 14 that had been recommended for replacement; it had inadvertently not been replaced. While this was a highly undesirable occurrence, it did illustrate the accuracy of the assessment predictions: a tube had been identified as at risk of imminent failure and that tube did indeed fail within the next operating period.

**Case study: detailed analysis**

Part of the LifeQuest reformer offering involves attendance onsite of a highly qualified assessment engineer at the time of the inspection. The objective of this service is to provide sufficiently detailed analysis of the inspection data as it is obtained to identify those tubes that are at risk of failure before the next scheduled outage. The speed of this analysis permits replacement of those tubes before the restart of the plant. In the event that insufficient replacement tubes are available or the replacement would adversely affect the outage schedule and the restart, the information permits informed decision making as to the risk.

A LifeQuest rapid assessment was undertaken for inspection data obtained from a reformer furnace, which for very sound process reasons, was operated at well above average operating temperatures and consequently tube life was typically of the order of 10 years or less. Three tubes were identified as at high risk of failure and recommended for replacement before restart of the plant.

An output of the LifeQuest reformer process is a calculated failure date for each tube. In line with API recommendations however, a recommended replacement date is provided and this is set at 80% of the life from commissioning to calculated failure date. It is considered that tubes operating at greater than 80% consumed life are at significant risk of failure. Because of scheduling and related issues, the plant owners opted to accept the risk of tube failure and chose not to replace these three tubes. One tube subsequently failed online, necessitating a plant outage at which time all three of the at-risk tubes were replaced. Subsequently, a full LifeQuest reformer assessment was undertaken on the inspection data and identified a further 15 tubes to be replaced at the next scheduled outage. Given the past experience, the plant owners scheduled replacement of those tubes.

**Case study: burner management**

A LifeQuest reformer assessment was undertaken on inspection data obtained from a side-fired reformer on an ammonia plant. The inspection noted that a few tubes appeared to be significantly bulged. An example of this is shown in Figure 7. The data illustrated in Figure 7 shows two consecutive inspections. It can be seen that diameter growth (creep) is occurring rapidly in the area of the bulge and the separation between the two datasets is significant. Elsewhere, the rate of growth is more modest. It was determined that this bulge was directly opposite a radiant wall burner.

A particular value of the inspection was the identification of undesirable heat distribution. The LifeQuest reformer assessment put the level of risk into

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**Figure 8. Tube profile showing unusual growth at the top of the tube.**
temperatures however show a tendency to suggest that the exceed the average by approximately 20˚C. The measured show good agreement with the maximum tube temperature, The calculated tube metal temperatures at this location was then compared with plant pyrometer IR measurements. be expected.

assessment indicated that replacement would not be this location had occurred in the previous 18 months. This were of the opinion that these hot spots had only been commissioned. However, in this case, the plant operators that previous damage has accumulated since the tube was a few tubes leading up to the outage. It was reported that the hotspots had been near the top of the reactor. The plant had undergone a significant debottlenecking exercise during the turnaround. This had an impact on the furnace, and was expected to result in an increase of approximately 20˚C in operating temperatures during subsequent operating periods. A critical issue therefore was to understand the impact of this temperature increase on the remaining life of the tubes. The LifeQuest reformer has the capability of assuming changes to operating conditions in the future. As noted previously, the analysis does not require plant temperature data as an input to the assessment. The software will calculate an effective temperature at which the tube has operated in order to generate the level of creep strain that is measured during the inspection. In most assessments, that same creep effective temperature is used for future operation. In this case, the plant owners specifically requested that the effect of a 20˚C increase be assessed. This was undertaken and no tube replacements were recommended before 2021. This result provided confidence that the plant debottlenecking exercise being undertaken would not impact adversely on the safe and reliable operation of the reformer.

The plant inspectors had noted hot spots near the top of a few tubes leading up to the outage. It was reported that the hotspots had been present for approximately 18 months. The inspection data did indeed show the consequences of these hotspots (Figure 8). The LifeQuest predictive facility assumes that previous damage has accumulated since the tube was commissioned. However, in this case, the plant operators were of the opinion that these hot spots had only been present for approximately 18 months. The assessment was therefore undertaken by assuming all the creep damage at this location had occurred in the previous 18 months. This assessment indicated that replacement would not be recommended before 2024. If the hot spots were eliminated, longer lives, at least based on damage at this location, could be expected.

The calculated temperature data from the assessment was then compared with plant pyrometer IR measurements. The calculated tube metal temperatures at this location show good agreement with the maximum tube temperature, exceeding the average by approximately 20˚C. The measured temperatures however show a tendency to suggest that the central tubes are running hotter. It is well known that

Case study: problem solving
A reformer on a large manufacturing complex had operated reliably and conservatively for 10 years. Inspection and life assessment of the tubes was undertaken with some specific questions in mind over and above the fundamental issue of tube life. The plant was undergoing a significant debottlenecking exercise during the turnaround. This had an impact on the furnace, and was expected to result in an increase of approximately 20˚C in operating temperatures during subsequent operating periods. A critical issue therefore was to understand the impact of this temperature increase on the remaining life of the tubes. The LifeQuest reformer has the capability of assuming changes to operating conditions in the future. As noted previously, the analysis does not require plant temperature data as an input to the assessment. The software will calculate an effective temperature at which the tube has operated in order to generate the level of creep strain that is measured during the inspection. In most assessments, that same creep effective temperature is used for future operation. In this case, the plant owners specifically requested that the effect of a 20˚C increase be assessed. This was undertaken and no tube replacements were recommended before 2021. This result provided confidence that the plant debottlenecking exercise being undertaken would not impact adversely on the safe and reliable operation of the reformer.

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infrared (IR) measurement technologies may suffer errors due to issues such as path length and reflectivity. It is suspected that the IR measurements techniques on this site would benefit from the application of correction software to improve accuracy.

This case study illustrates the abundance of useful information that can be derived and tailored to address specific issues and problems.

Case study: timely decision making
An operator had performed reformer tube inspection repeatedly over a number of shutdowns. Despite the evidence from these inspections showing steady and consistent growth in the tube diameters, the owners had not previously elected to quantify the impact of the inspection results in terms of remaining life assessment. A rapid assessment was undertaken at the time of the latest turnaround at which time the inspection data revealed that significant creep strain had occurred. This assessment indicated that 17 tubes would not survive until the next outage. Since this information was not previously available, the plant had not made time available within the turnaround window to replace this number of tubes and only eight tubes were replaced. These findings have required the development of a management plan to closely monitor and control, process and tube temperatures. LifeQuest reformer has since been used to undertake a ‘what if’ sensitivity analysis to understand the risk associated with temperature control allowing the plant operators to set in place integrity operating windows and action plans to maintain operation with those limits.

This case study illustrates the power of the assessment and inspection package to assess risk and develop operation plans to guard against unscheduled tube failure. It also illustrates the importance of understanding tube condition and risk of failure throughout the life of the furnace.

Conclusion
The preceding case studies clearly illustrate the advantage that a combined package of strain-based tube inspection and technically sound life assessment technology brings to the operators of steam reformer furnaces. In the absence of the knowledge that these technologies provide, plant owners are effectively operating in the dark, running the risk of tube failure and the high associated costs. Conversely, risk averse owners will operate under conditions where optimum production is not achieved, which may be equally costly. These technologies allow informed decision making and represent an essential component of any asset integrity management plan for syngas plants. 

References