INTRODUCTION

If you have a coke drum, you may or may not be in a smiling mood. Coke Drums can be a very severe operation that leads to a lot of cracking, distortion, and headaches. On the flip side, they are also integral parts to generating revenue at a refinery with the ability to break down heavy crudes.

Much of the focus in industry has been on measuring physical aspects of these drums (e.g., temperature, strain, laser scanning), but not as much attention has gone into figuring out exactly what to do with this information. E²G has developed some unique methods for extracting as much useful information out of this data as possible and is incorporating this information into damage models that can predict the rate of damage accumulation for different proposed operating scenarios. This information, when coupled with a suitable cost-benefit financial analysis, can help to determine the optimal scenario for balancing production with maintenance in order to maximize profit.

BACKGROUND - COKE DRUM OPERATION

Coke drums are, quite literally, a messy business but show up in many refineries around the world as a means to break down heavy residual hydrocarbons into lighter ends that can be refined into more useful, profitable products. As a byproduct of the process, petroleum coke (pet coke or simply coke) is formed—a valuable fuel source and steelmaking additive.

Following is a simple description of the typical operation of a coke drum:

1. At the start of the cycle, the drum is sitting empty and is relatively cool. There may be some steam in the drum.

2. Superheated, heavy residual hydrocarbons are introduced into the drum from an external furnace.

3. These heavy hydrocarbons “crack” into lighter hydrocarbons that exit the drum through the overhead. A byproduct of the cracking is petroleum coke (pet coke or simply coke), which is almost pure carbon.

4. There comes a point where the rate of continued cracking within the drum is too low due to the increased amount of coke
and lower temperatures. At this point, the heavy hydrocarbons are switched to the standby drum (typically there are two coke drums for each delayed coking unit operating in parallel).

5. The drum that has just finished its cracking phase is cooled very quickly (quenched), typically using steam, water, or both. This cooling process results in significant thermal gradients in the pressure boundary. This is the phase that leads to the most damage.

6. Once the drum is depressurized and cooled such that the coke will not self-ignite, its contents are “dumped” to clear it out in preparation for the next cracking cycle.

7. Typically, water jets are used to remove residual coke from the drum walls. The necessity and operation of these water jets depend on the type of coke formed.

Often, the time it takes to complete the above steps on a single drum, referred to as the cycle time, is minimized by operators to increase throughput. Typical cycle times are anywhere from between 10 hours to 30 hours. This extreme cycle of pressurization and heating during initial cracking followed by depressurization and quenching prior to dumping the contents is severe enough to greatly reduce the useful life of the drums themselves. The damage is worse for shorter cycles. Typical damage is accumulated in the form of distortion (e.g., bulging, ratcheting) and cracking. If a crack is discovered (usually at the welds), the coke drum needs to be taken out of service and repaired (typically while the other drum is still in operation). As the drum ages, cracks occur more frequently, repairs become more common, and eventually the drum needs to be replaced because the cost of keeping it in service is too high.

It is common to perform laser scanning to view the changes in the drum’s overall diameter and any additional local distortions that might be present. However, the deliverables from these measurements are not typically used within a fundamental predictive framework to make better decisions regarding life extension. This is evidenced by the recent API coke drum survey, which indicates that only 20% of respondents utilize this measured data to make informed decisions to predict cracking, evaluate the need for repairs, or optimize operation.

To date, there are no standard methodologies developed in the refining industry for coke drum life prediction, as evidenced by the current draft of API Technical Report 934G as well as by the limited analytical work performed to validate a coke drum during the design phase. Simplified approaches have generally been used to define trends rather than develop more fundamental analytical insight into structural response. Out of necessity, operators have gone the route of taking online measurements of temperature and selected strains to better understand the physical manifestations of the operation on the drums in an attempt to comparatively improve their operating practices, mainly with regards to the quenching phase. Of the recent literature on coke drums, the 2010 Journal of Pressure Vessel Technology paper by Xia, Ju, and Du Plessis [1] provides one of the more insightful analyses of thermal structural behavior. Independently, E2G has been evaluating the coke drum problem and proposes a similar simulation-based modeling approach, but with a variety of further refinements that we will briefly discuss here.

**E2G’S APPROACH**

It is well-known that coke drums are subjected to severe operating conditions that lead to damage in the form of progressive plastic strain accumulation and fatigue cracking; however, the difficulties of performing an insightful, meaningful coke drum analysis lie hidden beneath the surface. There are a variety of uncertainties and randomness in temperature and stress during the quench portion of the cycle that limits the value of a conventional, deterministic analysis for life
prediction. Further complicating the issue, the progression of damage can involve gross plasticity, permanent dilation, and variable bulging in drums. There are also hot spots that sometimes appear randomly on different parts of the drum surface. Additionally, the accumulation of damage is history (path) dependent, meaning that how you got to the damage is as important as the snapshot you have at any point in time.

So what really is the end goal with coke drum management?

We don’t really feel that the end goal is just the determination of expected damage and remaining life, but a better understanding of operational risk (and therefore costs) in order to maximize overall profit.

Think of the goal as extracting as much benefit as possible from the drums over their entire lifetime rather than just predicting “life” itself; you may be fine with determining minor repairs that result from your chosen operating cycle, even if it reduces the overall life, because in the end, you still come out ahead. However, there needs to be a balance between maintenance and productivity. Our analysis takes into account an underlying profit logic that includes considerations of throughput, productivity, repair effectiveness, and/or minimizing damage accumulation.

Most everyone involved with coke drums understands that the rapid quenching at the end of the production cycle is particularly damaging. A shorter cycle time will intuitively lead to more damage, but exactly how much more damage would one expect from running a 20 hour cycle versus an 18 hour cycle or an 18 hour cycle versus a 16 hour cycle? Would one expect the same factor of increased damage?

The big picture is that with a shorter cycle time, more cycles can be completed within any given time period (yearly), producing more product and increasing the short-term revenue. The cost is increased damage, higher maintenance costs and, possibly, a shorter overall life. A shorter cycle time (faster quench rate specifically) leads to more damage. A trade-off decision needs to be made: reduce the cycle time to produce more product and increase the short-term revenue but not so much that the cost of repair becomes too high or the reduction in the overall life of the drum due to accumulated damage over many cycles becomes too great. For example, by running a 16 hour cycle versus a 24 hour cycle, the total number of cycles for a coke drum over its entire life (before it is replaced) might be 2,500, whereas for a 24 hour cycle, it might last up to 3,000 cycles or more. Thus, a shorter cycle might lead to short-term gains, but at the expense of a shorter overall life and less total profit over the entire life of the drum. If you factor in repair costs, this decision gets even more complex.

To develop the required understanding to make these informed decisions. E2G has developed the following six-step approach:
1. **Personalized Data Review:**
   We review all the historical data for YOUR drum, including repair history and operational procedures in order to explain how your drum has operated over time. We stress “your” drum, because this first step focuses on your specific cycle, material of construction, coke type, and cost scenarios and not that of a generic coke drum. It is very important to put all of this into context in order to make the right decision.

2. **Probabilistic Thermal Modeling:**
   Once we have an understanding of your drums, we develop thermal simulation models that account for the “randomness” of your process (thermal profiles that result from how you heat up and quench) and how these profiles and associated fluid flows interact with your type of coke (gravel or boulders). Specifically, E2G’s research group has developed a unique probabilistic approach to determining the heat flux distributions within the drum solely from measurements of temperature on the outside by solving a probabilistic thermal inverse problem using a new approach that we have devised. Consider that when you measure external metal temperature, there are a large number of potential combinations of internal temperature distributions that could result in this measurement; however, by performing a careful mathematical analysis of this time-dependent data, the range of possible heat flux distributions can be bounded, and this uncertainty can be quantified. Understanding this variability and accounting for it in our models is critical. To get a more technical description of this approach, see our recent paper on this topic, presented at the 2015 ASME PVP meeting [10]. The random appearance of hot spots is also taken into account and characterized probabilistically.

3. **Scenario-Based Damage Modeling:**
   Once the thermal distributions are well understood, we can import this information into our stress analysis models to predict damage. A nonlinear finite element model (FEM) is used to simulate the response to various loading scenarios throughout the operating cycle of the drum (e.g., fill, crack, quench). ASME Code elastic-based fatigue methods previously used for coke drum assessments are technically invalid when ratcheting (incremental plastic
strain accumulation) is occurring. More modern fatigue methods and damage models are required to address the permanent irreversible damage and material degradation produced during cycling. Material damage models that include cyclic plasticity effects are essential in obtaining any form of realistic behavior.

4. Validation With Real Measurements: Understanding and simulation can get you a long way; however, it is prudent to validate (or tune) the models prior to using them for prediction. This can be achieved by obtaining specific data (e.g., temperature) from your drums while in operation. While this may seem similar to what industry is already doing, there is one key difference. Having increased the understanding of these drums through simulation, the locations for data gathering can be strategically placed at points of highest interest rather than just spreading a wide net of thermocouples indiscriminately. This allows us to get the most information from the least instrumentation.

5. Prediction of Maintenance Costs: With understanding, simulation, and validation comes the ability to make predictions of potential damage, as with many other engineering models. The ability to make predictions allows for the development of operational cost models (profit logic) and a better understanding of coke drum health in general. Specifically, our integrated approach leads to a tool that is able to predict the rate of damage accumulation up to critical levels (which translates to the need to repair the damage and pay for those repairs) for a variety of different operating scenarios. This is done probabilistically, because it is difficult to make absolute predictions for problems that involve so much uncertainty.

6. Better Decision Making: Better decisions can be made by factoring the costs predicted by our models due to increased maintenance for scenarios that may superficially seem to be better by increasing throughput. Consider the similarity to other risk-based approaches: the consequence of failure (damage requiring a repair) on a coke drum is understood by many, but our comprehensive predictive models give you further insight into the probability of failure and what this means in a larger context that also accounts for all financial considerations. With consequence and probability comes the ability to predict and, ultimately, manage risk. Insight into operational changes and their effects allow for a better understanding of repair costs versus product yield that will allow for the optimization of overall profit. Even if your operating process calls for pushing the drums hard to maximize short-term yields, by understanding that you will take on more damage and be able to quantify the amount of extra damage, you will be able to make the proper cost/benefit tradeoff.

Of course, no predictive model is perfect, and there will always be some uncertainty in the results. The total number of cycles cannot be predicted to an exact number with any method. However, even though absolute deterministic predictions are not possible, relative probabilistic predictions are. It is these relative changes that are most important to the decision-making process. For example, if the cycle time is decreased by two hours, how much will this affect the overall life compared to before, and how will this affect overall profit as well as short-term profit, which may be more of a concern? Relative changes can be used for optimization purposes. Sometimes, decreasing the cycle time is the right answer even if more damage occurs, because that damage is manageable and paid for by the increased revenue that can be made by compressing more cycles into the same time period.

E²G’s approach leverages our expertise in simulation modeling, advanced material modeling,
and sophisticated mathematical/probabilistic methods to develop a comprehensive decision-making framework for coke drum life cycle management. Additional expertise and research in a number of related areas has positioned E2G very well to solve the “coke drum problem.” If you have a coke drum that you are concerned about, let us know. We would be more than happy to take a look and offer our suggestions for improvement. We will help you determine the best operating cycle for your coke drum in order to optimize your own operations and maximize your profit, tailored to your specific circumstances and priorities. If you currently have a crack or other damage, we can also help you determine whether it is safe to operate until the next shutdown or whether you should take action sooner than that. **Maximizing your profit; does that make you smile?**

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**MAXIMIZING PROFIT**

In simple economic terms, one might want to choose the optimal cycle time in order to maximize some measure of profit, whether this is the profit-per-year or the total profit over the lifetime of the drum. By choosing a shorter cycle time, more cycles can be completed within any fixed period of time (yearly), which increases the revenue from production over that period. However, by decreasing the cycle time, more damage is done to the drum, which will lead to an increased rate of repairs; and the cost of these repairs, as well as potential loss in production while these repairs are being made, both serve to lower the overall total profit. At some point, the repairs become so frequent that it no longer makes sense to continue operation, and the drum will be taken out of service for significant repairs or replacement. The optimal cycle time is one for which the gains due to increased production still outweigh the increased cost of maintenance and repair. This is represented conceptually below where the optimal cycle time is determined to be around 14 hours (an illustrative example that is not meant to be taken literally).

In the most general terms, the profit logic can be written as:

\[ \text{Profit} = \text{Revenue} - \text{Costs} \]

The total revenue over the lifetime of the drum is just the revenue earned per cycle \( R_c \) multiplied by the number of cycles \( N_T \).

\[ \text{Revenue} = R_c \cdot N_T \]

Similarly, the total cost \( C \) can be written as the sum of the initial fixed cost of purchasing the equipment, installing it and starting it up, \( C_F \), and, the sum of all the maintenance and repair costs for each month of operation, \( C_i \), up to a total of \( m \) months of operation (after \( m \) months, the coke drum is assumed to be taken out of service).

\[ C = C_F + \sum_{i=1}^{m} C_i \]

Using these simple relations, one can start to see how a mathematical model (profit logic) could be developed that allows for optimization. The monthly repair costs include regular, planned maintenance
plus unexpected occurrences (e.g., having an unplanned shut down to repair a crack). Our more-detailed financial analysis considers repairs and cycles per month, the availability time each month (considering downtime for repairs); revenue per month (accounting for loss of production due to unplanned shutdowns); and ultimately the profit per month, per year, or over any other time period of interest.

Although this analysis can get quite complicated, one thing we can say for sure is that in order to maximize total profit over the lifetime of the coke drum (get as many cycles as possible out of a single drum), a longer quench time is better, since shorter quench times lead to larger stress and strain ranges, which inevitably lead to shorter fatigue lives (less cycles until failure). However, a longer quench time stretches this larger profit out over a longer period of time, which effectively reduces the amount of profit made in any one year. So, if yearly profit is what you want to maximize, one would think that shorter quench times would be better; and if fatigue weren’t an issue, the shorter the better.

However, shorter quench times will inevitably lead to more repairs, a shorter drum life (both in terms of calendar time and the total number of cycles), and possibly more downtime and loss of production to replace the drum more frequently. All of this and more needs to be taken into account in order to figure out what the best cycle time is for your particular priorities.

Do the number of repairs from previous months predict the number of repairs going forward? Understanding your drums will help to predict the rate of repairs and how this may change moving forward depending on your chosen operating conditions. Assumptions and, ultimately, probability distributions can be used to predict the revenue relating to yield (as the price of oil changes).

Future repair rates depend on the previous number of cycles, the cycle time (quench rate in particular), the previous number of repairs, and the type of each repair. This will be covered in more detail in a future insights article...stay tuned!
REFERENCES


