The influence of maintenance on the life cycle of above ground storage tanks

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Abstract

In supply chains such as those in the petrochemical industry, the above ground storage tank (AST) plays an important role in ensuring a continuous flow of product and these like other components must undergo regular maintenance. While maintenance on the majority of surfaces of the typical AST can be conducted when in its normal operational condition, the AST floor presents a particular challenge because of its inaccessibility. As a consequence the tank has to be periodically emptied and made out-of-service to conduct inspections and repair work deemed necessary. This is a costly activity both in terms of loss of earnings and the maintenance operation itself.

This paper addresses this situation and in particular looks at the operation of the AST together with the current limitations and possible enhancements to maintenance. The focus is on the AST floor as this is the primary component that characterises the out-of-service interval, an interval that needs to be minimal in terms of both duration and frequency. Strategies to achieve these goals are presented.

Index Terms: Above ground storage tank, AST, floor inspection, life cycle, maintenance.

1. Introduction

An important goal of any supply distribution system is to meet the demands of the consumer and to do so in a timely and cost-effective manner. To achieve this goal a balance between the source and consumer, or supply and demand is required. This balance is achieved by forms of storage units that essentially counter any short-term fluctuations that might occur in the supply or demand.

The utility industries provide interesting cases of supply chains because they are all of a continuous nature; their products of water, electricity, gas and oil all have the common characteristic of continuous flow: 'turn on the tap and the product flows'. The case of electricity is a particularly interesting one since an energy conversion is required to facilitate storage and this is commonly achieved via hydroelectric pumped storage schemes.

The continuous flow of product within the utilities accentuates the need for an immediate balance between supply and demand and tends to place even greater importance on the storage units in terms of immediate availability and reliability, inevitably at an increased cost of the product.

In the case of the petrochemical industry, storage units are usually in the form of above ground storage tanks (ASTs). These tend to vary in size, with larger ones nearer the source and smaller ones towards the consumer, reflecting the relative supply and demand capacities across the chain. Furthermore, petrochemical products can be hazardous and can cause damage to the surrounding environment, increasing the importance of supply chain integrity. This integrity is improved by appropriate maintenance programmes and is the topic of this paper; the focus is on ASTs, their life cycle and associated costs.

Maintenance can be classified as either in-service or out-of-service. The former is preferred because the costs attributed to maintenance can be offset by the fact that the component itself remains in a productive, revenue earning state. Maintenance encompasses inspection and repair, with the overall aim to maximise safe operation and minimise any disruptive events that could lead to a loss of service, all within a cost-effective manner.

Advanced technologies for condition monitoring and inspection are likely to play increasingly important roles in this context; they can be considered as components within 'e-maintenance', a term defined recently by Crespo-Marquex and Iung [1] as "maintenance support which includes the resources, services and management necessary to enable proactive decision process execution".

This paper presents an analysis of the inspection and repair operations applied to ASTs and their influence on overall productivity. A key factor here is the current need for out-of-service maintenance, brought about by the content and structure of an AST and in particular, its floor. Clearly, any such out-of-service intervals can be viewed as 'dead-time', non-productive and incurring significant costs. The underlying reasons why out-of-service remains necessary are presented here, together with a life cycle model. This is followed by an analysis of the life cycle model aimed at increasing the overall productivity across the lifetime of an AST.

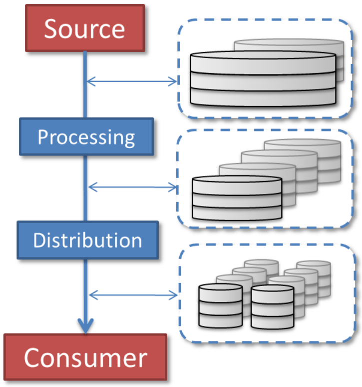

Figure 1: Outline of the source to consumer supply chain in the petrochemical industry showing above ground storage tanks (ASTs) grouped in farms. Generally, their size decrease and their numbers increase the further down the chain.

2. AST characteristics

ASTs range in size from around 120 meters in diameter with capacities as large as 1 million barrels, down to the region of 6 meters diameter storing just a few hundred barrels. Their capacity tends to decrease as they become closer to the consumer while their numbers tend to increase, as illustrated in Figure 1 which shows tanks in small groups known as farms.

On a global scale, the tank storage capacity at the processing stage as of May 2010 was approximately 2.75 billion m^3 which equates to a buffer capacity equivalent to approximately 60 days of global consumption [2]. Given normal world-wide production rates, it would take some 60 days to fill the available buffer capacity assuming there was no consumption; and conversely, assuming there was no supply and full storage, the same duration to empty it.

The predominant parent material used to build ASTs is carbon steel, the critically important factor here being its very high strength to cost ratio. However, the major drawback associated with carbon steel is corrosion and this in turn impacts on maintenance schedules and the overall life cycle of ASTs [3]. It has been reported that for a new tank, corrosion normally becomes an issue after around 15 years [2].

As such, guidelines from API [4] or EEMUA [5] recommend out-of-service maintenance frequencies as often as every 3 years but more typically every 10 years.

As with any component in the distribution network, the question arises as to whether maintenance can be undertaken while *in-service* or if it is necessary to take a given component *out-of-service*. In addressing this question, criteria such as safety, costs and accessibility are important factors.

The AST presents a particularly interesting case and while access is possible to the majority of the external surfaces, the floor of an AST presents a major challenge. First, access to the floor from beneath is impracticable, simply because of the weight and geometry of many ASTs; this is especially true when a tank contains product, making it even more difficult to raise from the ground. Thus in practice access to the floor is from within the AST, which in turn currently demands out-of-service periods for its maintenance. Such periods are costly and thus there is significant interest in reducing both their frequency and their durations.

Of course, an out-of-service tank has a direct impact on the supply chain balance, calling for an increase in the total number of ASTs to maintain the supply balance, further adding to the cost of out-of-service maintenance. The remainder of the paper focuses on this aspect of maintenance, with an emphasis on strategies to enhance overall AST productivity.

3. The AST life cycle

The AST life cycle is illustrated in the diagram in Figure 2. It begins with the installation and commissioning and ends with the complementary decommissioning. Within these two limits, the operational life of the AST is spent in a repetitive loop of in-service followed by out-of-service periods.

Figure 2 shows three conditions to exit the in-service condition, namely:

(i) Monitored

(ii) Scheduled or

(iii) Disaster.

The monitoring system shown as option (i) utilises technology that continuously monitors the condition of the AST and this information is then used to either bring forward or to extend the nominal period of in-service operations. Examples of such technology include the early work of Schempf [6], who in 1994 proposed amphibious robots to scan the AST floor.

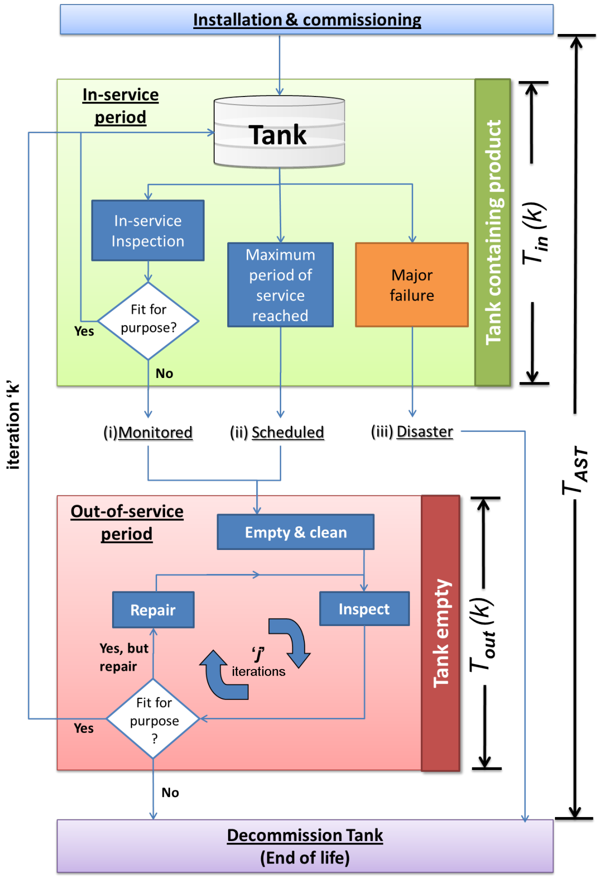

Figure 2: The AST life cycle: after the initial commissioning come 'k' iterative loops of in-service followed by out-of-service cycles which repeat until the tank is finally decommissioned. The operational lifetime of the AST is denoted by T_{AST} and the periodic in-service and out-of-service intervals at iteration 'k' are represented by $T_{in}(k)$ and $T_{out}(k)$ respectively.

Cruz and Ribeiro [7] in 2005 extend the amphibious approach to include internal inspection of the tank wall with ultrasound technology.

Sattar et al. [8] in 2007 continued this theme of amphibious inspection with focus on welds and cracks.

The information from these and other non-intrusive monitoring systems (e.g. acoustic emissions: Riahi and Shamekh. [9]) can assist in out-of-service scheduling and corresponds to the first route,(i) Monitored, in Figure 2. Optimisation of the out-of-service period is the primary subject of the remainder of this paper.

Returning to Figure 2 and taking route (ii) into the out-of-service state, here the AST has not been continuously monitored and is shut-down on routine schedules. The out-of-service frequency is normally chosen using guidelines such as API [4] or EEMUA [5] and varies based on the environment and nature of the stored product.

Finally, route (iii), labelled 'disaster', reflects the situation where a major failure has occurred or is predicted to be likely and the tank is judged to be uneconomic to repair and so is immediately de-commissioned.

An out-of-service period begins with emptying and cleaning the tank followed by an inspection which, as shown in the lower half of Figure 2, has three possible outcomes, namely the tank is either:

- fit-for-purpose and can be re-commissioned,
- fit-for-purpose after (further) repair or,
- not fit-for-purpose, (further) repair is deemed uneconomic and the tank is decommissioned.

When the tank is relatively new, at the very first iteration of this maintenance loop, the inspection might indicate the need for only minimal maintenance after which the tank is deemed fit-for-purpose and returned to service. Subsequently the inspect and repair cycle might be iterated more than once before the tank is returned to service; this is indicated by the 'j' iterations in Figure 2. Clearly, there are efficiency savings to be gained here with improved technology and quality of maintenance. These topics are addressed in the following sections.

The lifetime of an AST is made up of an iterative cycle of in-service followed by out-of-service periods. An example of a complete lifetime coming from rolling out this cycle is shown in

Figure 3 where the lifetime is shown as a series of in-service durations plotted against a corresponding series of out-of-service durations. Note the $10 : 1$ ratio in the time scales of the two axes to illustrate the approximate $20 : 1$ ratio between the overall durations of the in-service and out-of-service, reflecting the fact that the tank might expect to be out-of-service for 5% of its total life.

The in-service periods are shown as vertical sections (the first case is coincident with the vertical axis) and the out-of-service periods are shown as horizontal sections. Each pair corresponding to one iteration, k, on the life cycle diagram in Figure 2. Note that when $k = 1$ there is likely to be a longer in-service period and a shorter out-of-service duration than subsequent iterations, given that the tank is new and likely to require routine maintenance only, without any demanding repair work.

In Figure 3 an example of an extended out-of-service duration is shown immediately after the 3^{rd} in-service period, by the wider horizontal line ($T_{out}(3)$). The decision to take the AST out of service after a rather short in-service time could be made for example based on evidence from continuous e-monitoring [1]; and the corrosion detected could be severe enough to require substantial remedial work, or even the replacement of the whole AST floor. Such a situation occurring later in the tank life might well lead to the tank being decommissioned but in the example shown, decommissioning occurs latter, after 5 in-service periods corresponding to a total in-service duration in the region of 50 years, with a total out-of-service duration between 2 to 3 years. These years incur significant costs, impacting on the total productivity and profit over the lifetime of the AST. It is interesting to ask how these costs might be reduced in order to secure maximum return from the AST across its operational lifetime.

Clearly a key factor is to maximise the in-service time while minimising the out-of-service time; and to do so within an overall cost function. For example, if the carbon steel floor was replaced by a non-corrosive material with a similar strength but longer life, then out-of-service frequencies might well be reduced. However, today carbon steel has no financially viable substitute and while its material properties and protective coatings are continually improving, the profile shown in Figure 3 remains a typical one. Thus a material with the prime characteristics of steel, especially its cost and strength, but without its susceptibility to corrosion is called for; for this and for many other applications. Such advances would change the ratios and scales of the axes in Figure 3, reflecting greater overall productivity of the AST. Progress can also come from advances in maintenance and this is the focus of the remainder of this paper, with emphasis on how improved maintenance might improve overall AST productivity.

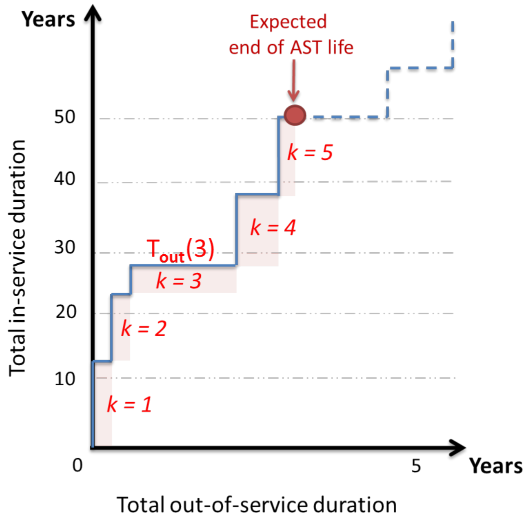

Figure 3: Total in-service time T_{in} versus the total out-of-service time T_{out}. Each step represents an iteration, k, within the AST life cycle from Figure 2. The vertical axis T_{in} and the horizontal axis T_{out} are scaled differently to accommodate a typical 20:1 in- to out-of-service ratio [4, 5]. $T_{out}(3)$ depicts a period of comprehensive out-of-service maintenance, entailing for example the replacement of the entire tank floor. Note that the expected end of AST life would likely require some form of inspection to determine if it is ready to be decommissioned and so a reduced out-of-service period when $k = 5$ is shown.

4. Out-of-service optimisation

The three main tasks associated with AST maintenance are shown in the lower part of Figure 2, namely the initial emptying and cleaning, followed by cycle(s) of inspection and repair. The fact that these operations are carried out while the AST is out-of-service has direct impact on the overall AST efficiency.

We consider here ways of improving the efficiency coming from both improved technology and working with parallel teams.

The three primary maintenance tasks, namely cleaning, inspection and repair are shown in each of the three rows, labelled (a), (b) and (c), in Figure 4. Each row shows a strategy for reducing the time of the maintenance task, $T_{out}(k)$. Consider first the three tasks in a wholly serial manner as shown in row (a). This reflects current practice where inspection and repair follow on from the initial cleaning phase. While retaining this serial structure then clearly savings could be made from reducing the times of the individual processes. So, given that the tasks are to retain the serial structure then speed-up must come from within the tasks (cleaning, inspection and repair), using improved technology and/or working in parallel teams.

As indicated in Figures 2 and 4, repair work is followed by another inspection, albeit perhaps limited to the localities of that repair work; so it is worth noting that improved efficiency might well come from minimising the number of these iterations (shown as loop 'j' in Figure 2(a)), and adopting a 'do it right first time' principle[1] to these tasks. Of course with any speed improvement there is an implicit and important assumption that the quality of maintenance should remain unchanged.

Figure 4 row (b) shows a level of parallel operations across the inspection and repair tasks. The requirement of inspection following any repair, as shown in row (a) of the figure, applies equally to rows (b) and (c) even though not explicitly shown for these two rows in the Figure. Note also that while parallelism could in principle apply also to the cleaning operation, it is likely to prove more difficult in practice due to the incompatibility of the initial AST cleaning operation with inspection or even repair work.

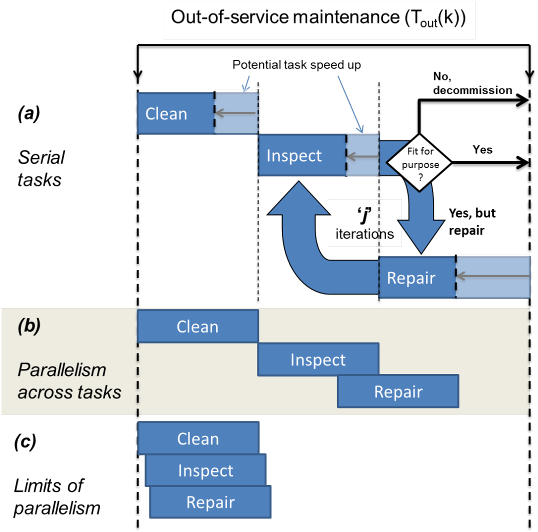

Figure 4: Potential configurations of the three main tasks of out-of-service maintenance namely cleaning, inspection and repair. In (a) the tasks are in series (with no time overlap); in (b) repair is shown to begin before inspection is complete and in (c) idealistic parallel operation is shown. The number of iterations of the inspect and repair cycle in (a) can be reduced aiming for a 'do it right first time' principle.

A potential improvement to the efficiency of this cycle could come from faster operations within each of the three tasks, cleaning, inspection and repair. The ideal scenario for example might involve longer cleaning periods to get better information from the inspection; the cleanliness of the AST floor is a crucial pre-requisite for inspection technologies such as magnetic flux leakage or ultrasound. It then follows that an inspection that takes longer to conduct but provides that much better information on the condition of the floor could in turn lead to improved repair work and maybe a more efficient approach overall.

An obvious example of faster operations is to employ multiples of the same or similar equipment. In all three tasks there is a possible cost/benefit trade-off coming from increased teams of equipment and manpower giving reduced times, against the loss of productivity while out-of-service. Thus, in-task parallel operations should be regarded as a primary avenue towards improving the overall efficiency of out-of-service maintenance. Also, reducing the count, 'j' of the inspect and repair loop (illustrated by the closed loop in Figure 4(a)) is another potential avenue for improvement.

In addition to in-task parallelism, further scope exists for parallelism across the three tasks. Currently, inspection and the corresponding production of the inspection report on which any subsequent repair actions might be taken, are essentially serial activities. Clearly there is capacity here for some level of parallel work, a good example being in the technology which underlies the inspection process, see for example the automated defect classification proposed by Ramirez et al [10]. This would mean that some level of repair operations could start soon after the beginning of the inspection phase without waiting for the more time consuming manual analysis.

Such efficiency savings are illustrated in Figure 4(b).

The limits of such parallel operations would also encompass the initial cleaning task, illustrated in Figure 4(c). However, the adverse environment immediately after emptying a tank calls for a major cleaning operation before any detailed inspection and repair operations can begin, certainly to the AST floor.

Beyond these forms of parallel operations, a truly major advance would come when the AST remains in-service for maintenance, including that on the AST floor and in particular repair operation.

Postulating the continuation of such advances leads ultimately to the possibility of an AST remaining in-service throughout its effective lifetime. While this might seem somewhat futuristic, nonetheless in the next section we consider the implications of such developments in the context of AST productivity and cost benefits.

5. AST Lifetime Productivity

Figures 2, 3 and 4 illustrate aspects of the AST life cycle, highlighting the two states of in-service and out-of-service periods. The out-of-service periods tend to be very costly: there is no income from the AST, i.e. from storage of product and there are additional costs from the maintenance operations themselves.

The potential avenues for improvement are self-evident, namely improve the quality of the original AST build and the quality of subsequent maintenance.

While time and quality might well be thought of as orthogonal they are clearly linked in that higher quality might well lead to longer maintenance times and higher costs. However, as described in Section 4, reduced times can come from strategies such as parallel operations and higher quality maintenance can come from advancing inspection and repair technologies.

Taking a longer-term view across an AST lifetime, a strategy might well be to maximise returns over the full

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[1] The 'do it right first time' or 'DRIFT' principle is applied in managerial accountancy that relates to delays in production and attempts to minimise their influence. Such a philosophy is analogous to minimise the maintenance period so that the AST can return to a productive in-service state. See: http://www.finbox.com/news-tools/financial-glossary/term/do-it-right-first-time-drift.

period, with maintenance a key dependent parameter within the strategy. This is illustrated in Figure 5 which shows five profiles of 'total profit' plotted against time, spanning a typical AST life. Each profile begins with the same initial cost C_0 comprising of capital, installation and commissioning costs.

Consider first profile (i). These linear segments correspond directly to those in Figure 3 but now with each pair indicating earnings (positive slope) and costs (negative slope), reflecting in-service and out-of-service periods respectively, and averaged over the corresponding intervals. As with Figure 3, four interval pairs are shown before reaching the end of the AST life. Note the longer duration of the 3^{rd} out-of-service period in Figure 5 corresponds to the T_{out} highlighted in Figure 3. Over the example lifetime of approximately 53 years, which includes all in-service and out-of-service periods, the total revenue generated is illustrated by the circle where the AST is decommissioned. Profile (ii) is simply a smoothed version of profile (i).

The steeper gradients of profiles (iii) reflects the influence of improvement in maintenance, coming for example from faster 'do it right first time' principle and parallel operations, discussed in the previous section and illustrated in Figure 4. In summary the improved efficiency of profile (iii) could result from:

- a reduction in the frequency of out-of-service periods,
- an increase in the quality of the individual tasks: cleaning, inspection and repair, or
- parallel operations.

An obvious goal for these advances in maintenance would be realised when there is no requirement for the AST to be out-of-service, giving potential for continuous earnings throughout its life. This situation is reflected here in the straight line profile, Figure 5 (iv), the slope of which would depend on prevailing conditions, including the costs of the futuristic advanced maintenance technologies that would operate under in-service conditions. Finally, profile (v) is included for completeness and represents the unlikely situation of the AST having no maintenance (and consequently a short life); here the difference in the gradients of profiles (iv) and (v) reflects the add-on costs of maintenance in the case of (iv).

Given these improved maintenance scenarios are conducted in a cost-effective manner, the overall time taken to reach the same profit margin as that of (iv) would be reduced.

6. Conclusion

Above ground storage tanks (ASTs) are a vital component in the supply chain of the petrochemical industry and as with any other component in the chain, maintenance is required to preserve its healthy operational condition. At present such maintenance requires out-of service operations, driven primarily by the AST floor and its relative inaccessibility. Out-of-service maintenance leads to significant costs. This paper has reviewed these costs and considered strategies to reduce them, analysed across the working lifetime of the AST. With this in mind we consider ways in which AST maintenance can be improved with the goal of maximising the AST efficiency.

Each of the maintenance tasks, namely cleaning, inspection and repair, have been considered in terms of time, parallel operations and quality. The paper explains how advances in technology that in turn improve service speed and quality can contribute significantly to improved efficiencies and higher lifetime earnings.

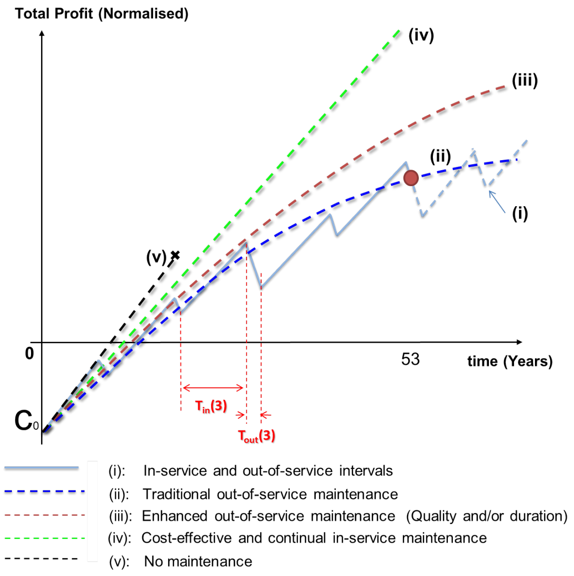

Figure 5: Total profit over the operational life if the AST in years. Each profile represents a different maintenance strategy. Early years show a loss given the initial capital costs represented by C_0. The unrealistic case of where no maintenance is available is shown by profile (v), with an early termination due to the tank being unsafe and deemed not fit for purpose. Profiles (ii) and (iv) dictate the state of current and the limit of the ideal maintenance respectively.

Finally, new materials with similar cost and strength characteristics to those of carbon steel, but with less susceptibility to corrosion, are sought. These might ultimately lead to the viability of in-service maintenance only, encompassing both inspections and repairs; the path to such advances is as yet unclear.

7. Acknowledgements

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8. References

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