SCR Catalyst Management Strategies – Modeling and Experience

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ABSTRACT

For coal-fired boilers equipped with SCR, catalyst contributes to a major operating expense. Strategies for minimizing catalyst cost while preserving system performance - generally referred to as catalyst management – are receiving greater attention. Approaches for managing catalyst can vary widely. Therefore, analysis of catalyst management strategies requires accurate predictive tools for assessing SCR system performance that have the flexibility to address a wide range of scenarios. These predictive tools may also be used to investigate performance issues that facility operators may encounter. However, until recently, operators have not had access to these tools, except through catalyst suppliers or consultants.

In this paper, various catalyst management strategies will be examined. Using software currently used by several power plant operators and SCR technology suppliers, we will illustrate some of the important considerations of a catalyst management strategy and provide an example of how catalyst management strategies can be evaluated with such a software tool.

Presented at Coal Gen 2003, Columbus, OH
August 6-8, 2003

INTRODUCTION

With more coal-fired power plants operating with Selective Catalytic Reduction (SCR), catalyst management is a topic that has gained increased interest. In this paper, the topic of catalyst management will be explored along with a tool that can be useful for analysis of catalyst management strategies.

A comprehensive approach to catalyst management goes far beyond simply planning for the next catalyst addition or replacement and performing the associated catalyst testing. A comprehensive approach extends beyond the simple objective of minimizing catalyst consumption over the plant lifetime. A comprehensive catalyst planning effort involves minimizing the catalyst costs while simultaneously optimizing the operation of the facility to achieve the lowest cost to produce power. As a result, it involves making trade-offs between catalyst consumption, the frequency and duration of outages taken for catalyst work, ammonia slip, NOx reduction, baseline NOx, parasitic pressure loss, and, of course, comparing catalyst regeneration versus catalyst replacement. Assessing these trade-offs in an efficient manner requires an interactive tool. Some of the trade-offs that can be assessed with such a tool are discussed below:

> Ammonia Slip – If your plant can tolerate a higher ammonia slip from the SCR than originally anticipated, it may be possible to reduce catalyst loading, extend the time between catalyst replacement events, or to increase the amount of NOx reduction that is possible from the facility.
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> NOx reduction – With NOx allowances having a marketable value, increasing the NOx reduction of the SCR may be worth exploring. However, increased NOx reduction comes at a price of increased ammonia slip, increased ammonia consumption, increased frequency of catalyst replacement, increase catalyst loading, or increased pressure loss.
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> Baseline NOx level – If the baseline NOx level is increased, this may have benefits to the boiler or improve ash LOI, but it this may necessitate higher costs associated with operating the SCR at a higher reduction level or it may have other adverse affects, such as higher ammonia slip. Alternatively, reducing NOx from the furnace to the SCR inlet can help reduce ammonia consumption, reduce ammonia slip, and permit longer times between outages.
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> Catalyst Loading – It may be possible to extend time between catalyst outages further through increasing the catalyst loading beyond the initial design level. However, increased catalyst loading adds catalyst cost and increases parasitic loads due to pressure drop across the catalyst.
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> Pressure Drop – In some catalyst management scenarios, some layers in the catalyst reactor are left empty. This approach has the advantage of reducing

catalyst loading and pressure drop versus a traditional approach that fills the SCR reactor and later replaces catalyst as the catalyst loses activity.

Furthermore, there are other effects that may need to be reassessed after a period of plant operation. For example, if catalyst deactivation rates differ from what was originally expected, it may be necessary to modify the plans for catalyst replacement or regeneration. In this paper we will explore such a situation in detail.

Because of these many trade-offs, a tool that enables the owner's personnel to quickly and easily evaluate different scenarios should be very useful.

In the next section, we will review catalyst management basics. Then, we will discuss the key features of a tool that is used for catalyst management by a number of power plant operators and SCR technology suppliers. Finally, we will discuss an assessment of catalyst management alternatives at a utility boiler using SCR.

CATALYST MANAGEMENT BASICS

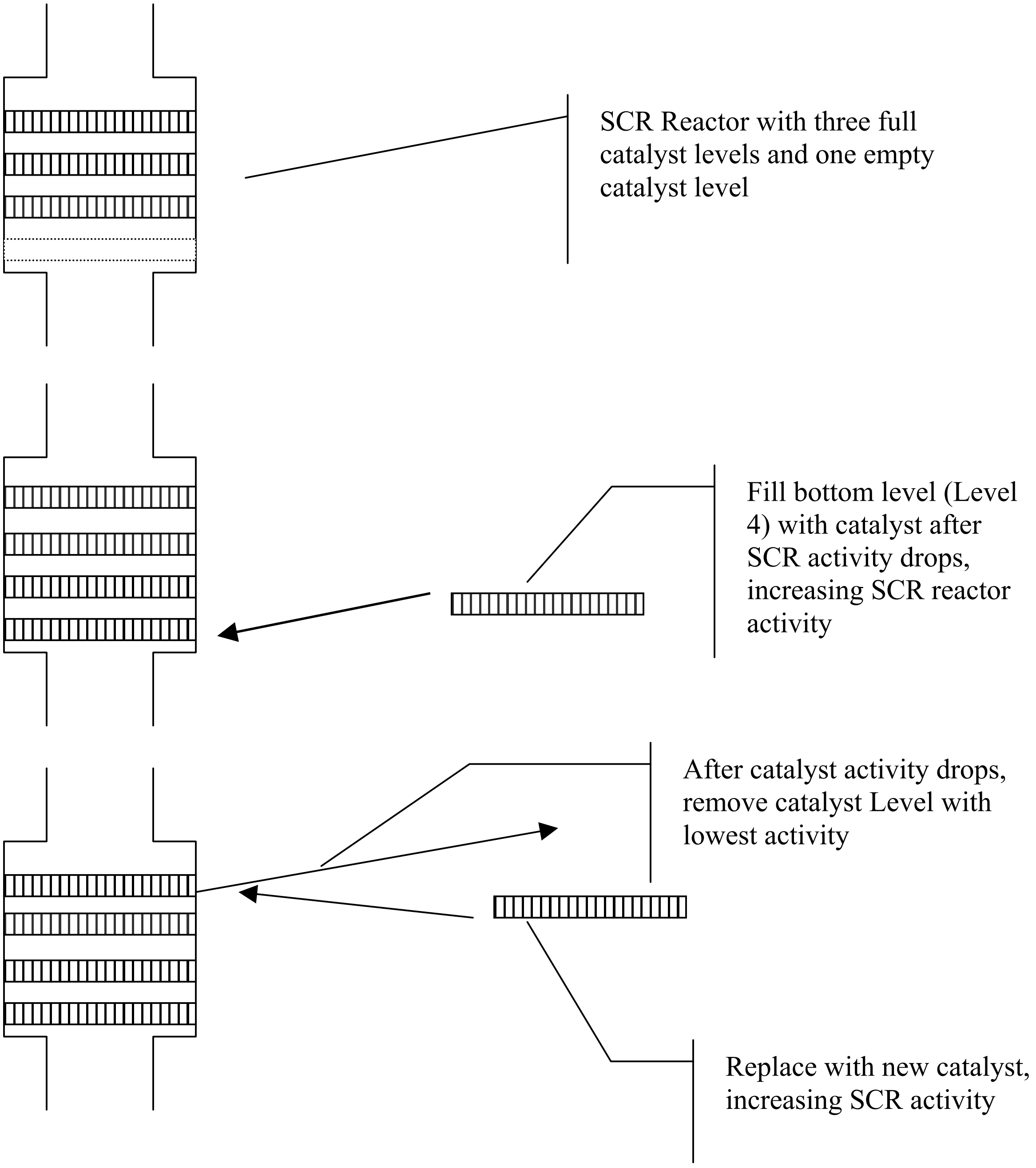
Although the physical size of catalyst should not significantly change over time, catalyst can be viewed as a consumable item. The catalyst has the ability to facilitate the NOx reducing reactions, and this quality is called "activity". Over time, impurities in the gas stream will deposit on the catalyst and block exhaust gas from reaching active sites within the catalyst. Some catalyst "poisons", such as arsenic, will chemically bond to the active vanadium pentoxide within the catalyst micropores. As more and more of these microscopic, active sites get blocked, the catalyst activity will gradually drop to a point where performance becomes unacceptable.

Each SCR reactor is designed to provide a minimum specified NOx reduction performance with a maximum ammonia slip under a given set of conditions after the catalyst has lost some portion of it's initial activity. Therefore, once catalyst activity drops below a level determined in the original design of the SCR system, it is necessary to replace some of the catalyst or add more catalyst to the reactor. SCR catalyst activity is regularly monitored by laboratory analysis of catalyst samples. This is normally done on an annual basis.

Most SCR reactors are designed with up to four available levels of catalyst. In some cases each level may hold more than one layer (two layers of catalyst essentially stacked on top of one another). When the system is new, with fresh catalyst, at least one level is typically empty, as pictured at the top of Figure 1. When the SCR catalyst activity drops to a point where ammonia slip increases to an unacceptable point, then new catalyst is added to level 4, as shown in the middle part of Figure 1. In the case of Figure 1, only one catalyst layer is in each level. But, in some cases two layers are in each level. In that case, one layer (half of a level) would be added to level 4 and then at a later time when SCR total activity is low enough, a second layer (half of a level) would be added to level 4, filling level 4 and the SCR reactor.

After the SCR reactor is full, it is necessary to replace catalyst levels with new or regenerated catalyst to increase total SCR catalyst reactor activity. This is shown at the bottom of Figure 1. Since the top level usually loses activity faster than the others, it is normally the first catalyst level to be replaced.

Figure 1. Normal Add and Replace Sequence



SCR Reactor with three full catalyst levels and one empty catalyst level

Fill bottom level (Level 4) with catalyst after SCR activity drops, increasing SCR reactor activity

After catalyst activity drops, remove catalyst Level with lowest activity

Replace with new catalyst, increasing SCR activity

Another approach to managing catalyst is to regenerate the catalyst. One approach, shown in Figure 2, requires that one level of catalyst always be empty. This permits the removed catalyst to be off site for regeneration. When total SCR catalyst activity drops to a minimum acceptable point, regenerated catalyst is added to the empty catalyst level and the catalyst level with the lowest activity is then removed for regeneration, as in Figure 2. When using this regeneration approach and two layers of catalyst are installed in each level, then it is necessary to remove the top layer for regeneration in one outage before removing the bottom layer during the next. Of course, regenerated catalyst must be first added to empty layers on the bottom before being added to the top. This approach, described in Reference 1, is currently being used at PG&E National Energy Group's Indiantown station.

The advantages of a regeneration approach such as this are:

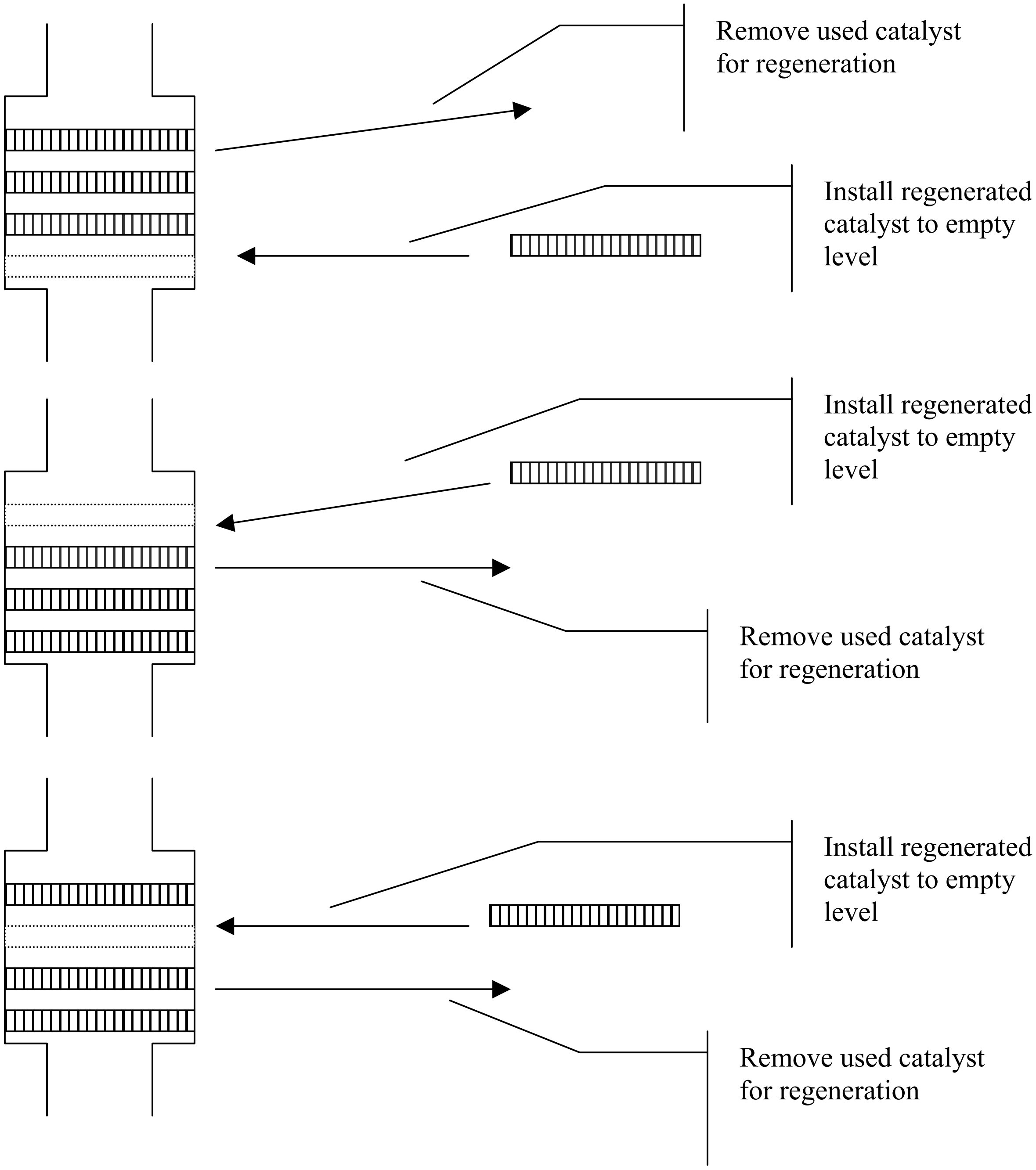
- If the catalyst is physically intact, it is not necessary to purchase new catalyst. And, since regeneration of a unit of catalyst is typically less expensive than buying new catalyst, savings are possible.
- Pressure drop across the SCR reactor is less than add-and-replace approaches that fill the SCR reactor, reducing the associated parasitic losses.
- Depending upon SCR reactor access and available staffing, shut downs for catalyst regeneration may be shorter in duration than for a catalyst level replacement because as one layer is removed for regeneration it may be possible to simultaneously install regenerated catalyst on another level.

There are some disadvantages of this regeneration approach with respect to a normal add-and-replace approach, such as:

- Shut downs for catalyst changes will typically be more frequent.
- A catalyst that is reactivated with new active material may not behave in the same way with respect to SO_2 to SO_3 oxidation and with respect to deactivation as the original catalyst because the active component (V_2O_5) may not be distributed throughout the catalyst in the same manner.
- If the catalyst is badly eroded, or otherwise physically damaged, regeneration cannot be performed and replacement with new catalyst is necessary.

Whether replacing catalyst or regenerating catalyst, it is important to identify the layer with the lowest activity and replace or regenerate that layer. This is because the ***net*** activity addition to the SCR reactor is the activity of the new or regenerated catalyst minus the activity of the catalyst that is removed. The greatest net activity addition will occur if the catalyst with the lowest activity is replaced or regenerated. In most cases, the top level of catalyst (in a down-flow reactor) loses its activity at the fastest rate. This is because it tends to be exposed to the highest concentration of impurities. However, there may be some cases where activity is lost at the same rate or faster in other layers. So, regular catalyst testing is an important part of any catalyst management program.

Figure 2. Sequence for Regeneration of SCR Catalyst



MODELING CATALYST MANAGEMENT PLANS

Analyzing the various trade-offs and approaches to catalyst management is best done with a computational modeling tool that can quickly estimate the effects of a different approach on facility operation and forecast the future sequence of events and the associated costs. As a result, the model needs to be both accurate and flexible. A list of important features is shown below.

The model should be able to:

1. Model either add-and-replace or regeneration approaches easily, predicting the sequence and time of future catalyst events for several years.
2. Allow modeling initial load of catalyst of any type from any manufacturer.
3. Model changes in catalyst manufacturer or type over time.
4. Determine the need for catalyst changing based upon user-selected preference of either time periods or reaching an ammonia slip or activity limit.
5. Properly select the catalyst layer to be removed and replaced under a wide range of scenarios.
6. Model at least four for more levels of catalyst with up to two layers of catalyst per level.
7. Model different deactivation rates per level, as top levels often lose activity faster than lower levels.
8. Model time-variant catalyst deactivation rates, as deactivation rates can vary with time.
9. Model different catalyst deactivation rates for regenerated or replacement catalyst versus original catalyst, as regenerated or replacement catalyst may behave differently than the catalyst it replaces.
10. Accurately predict ammonia slip over time.
11. Model the effects of maldistribution of the ammonia injection on ammonia slip. This is especially important for very high NOx reduction SCR systems where the risk of ammonia break-through can be high.
12. Model changes in catalyst loading for each layer from the initial SCR reactor design, because experience may make such a change in catalyst management plant necessary (an example will be discussed later).
13. Model new SCR systems or systems that have been in use for some time.
14. Permit updating of catalyst conditions and deactivation rates as data becomes available.
15. Calculate the costs of future catalyst changing events and make long-term cash-flow projections.
16. Accurately model the effects of changes in inlet or outlet NOx on ammonia slip and the catalyst management plan.
17. Model the impact of the catalyst management plan on draft loss and associated parasitic power costs.
18. Perform Net Present Value analysis of the plan over a period of time.

Costs associated with a catalyst management plan include the cost of catalyst itself and the labor associated with removing used catalyst and adding replacement catalyst.

Additional costs that must be considered are costs associated with parasitic power, costs associated with lost production when the boiler must be shut down for catalyst changing events, procurement and other overhead costs, and monitoring and testing costs. Thus, the cost is not strictly proportional to the catalyst volume affected, but there are costs that may be considered "per event" costs and costs that may be incurred continually (such as parasitic power). Furthermore, since a catalyst management plan has implications that will extend for many years, the effects of escalation and cost of money should be considered such that Net Present Value analysis can be performed.

In addition to the above features, in order for the model to be most useful for the typical user, a computer program should run on a Windows-based PC, have a familiar user interface, and be well documented. Fortunately, modeling software with all of these features was recently made available to users with the release of CAT MANAGER™ version 2.0. Several owners of SCR plants and SCR technology suppliers are currently licensed to use CAT MANAGER™ version 2.0 or the earlier version 1.0. In the following section, we will discuss the modeling of one facility with CAT MANAGER™ version 2.0 where it became necessary to modify the catalyst management plan.

Modeling Changes in Catalyst Management Plans

At times actual catalyst behavior does not correspond to expected performance. This will normally cause the facility owner to reevaluate their catalyst options. In such a situation, there is a benefit to having a tool that enables the owner to quickly reassess various options in light of new information on catalyst performance. Orlando Utilities Stanton Energy Center Unit #2 is an example of how the owner found it necessary to revise their catalyst management plan after a few years of experience. As a matter of disclosure, neither OUC nor the catalyst supplier used CAT MANAGER™ to perform the analysis for any decisions made thus far, although both have since licensed CAT MANAGER™. In this paper, our intention is to compare the results of modeling catalyst performance with CAT MANAGER™ against experience at an actual facility and demonstrate how this tool can be effective in helping make catalyst management decisions for the future.

Orlando Utilities Stanton Energy Center Unit #2 is a 468 MW Babcock & Wilcox dry bottom boiler that went into service in June of 1996. The unit is equipped with low NOx burners, overfire air, an SCR, ESP and a wet scrubber for emissions control. The SCR uses Argillon (formerly Siemens) plate catalyst. Based upon an expected coal analysis that had adequate free CaO (over 2.5%), a moderate level of arsenic in the coal, and no fly ash reinjection, a low gaseous arsenic condition was believed to exist and the catalyst management plan was developed accordingly. Table 1 summarizes the SCR characteristics and performance and Figure 3 shows the SCR reactor. Figure 4 from Reference 2 shows a graph of the original catalyst management plan for Stanton #2. For each of the four catalyst additions shown on Figure 4, one layer, or one half of a level of catalyst is added, to fill the SCR reactor with 740 m^3 of catalyst by around 90,000 operating hours. The SCR is intended for year-round operation, providing typically 8,000 operating hours per year.

As documented in References 3, 4 and 5, Stanton Unit #2 experienced more rapid catalyst deactivation than originally anticipated. This was determined to be a result of arsenic deactivation due to actual coal mineral conditions being different than those originally planned for the SCR catalyst design. Specifically, actual CaO in the coal was lower than originally anticipated, which contributed to increased deactivation from arsenic.

Table 1. Stanton Unit #2 SCR

- Uses Argillon (formerly Siemens) SINOx plate type catalyst
    - TiO2 based for arsenic resistance & low SO3 conversion (<1%)
    - Eastern KY Coal - Arsenic 22.2 to 113.2 ppm in coal and 2.5% to 3.5% CaO in ash
- SCR is high dust type positioned just downstream of boiler outlet
- Reactor initially charged with 2 full catalyst layers of 370 m^3 (13,100 ft^3)
- Two more empty elevations initially provided for future catalyst recharges
- Uses anhydrous ammonia at full load design rate of 230 lb/hr
- Total system design pressure drop of 3.42 in wg at full load
    - Guaranteed NOx removal rates with design boiler output of 0.32 lb/MMBTU:
        - Initial condition test down to 0.10 lb/MMBTU
        - Continuous rated down to 0.17 lb/MMBTU
        - All at <2 ppm NH_3 slip for design operating period of 24,000 hrs (3 years)

Catalyst deactivation, being faster than expected, manifested itself as high ammonia slip and lower catalyst activity. Ammonia slip was measured to be 8 ppm in June of 1998 by wet chemistry methods and 8.9 ppm in measurements later that same year.[Ref. 3] Since ammonia slip is normally the first indication of reduced catalyst activity, it is important for a model to estimate ammonia slip.

Figure 5 shows a comparison of predicted ammonia slip (using CAT MANAGER™ ver 2.0) at Stanton #2 versus actual measurements. Two predicted curves are shown. One approximates the originally anticipated ammonia slip assuming a constant deactivation rate. The other predicted curve shows the predicted slip using actual deactivation rates. The predicted curve was determined by using actual catalyst activity measurements to develop estimates of actual deactivation rates. The predicted curves also relied on other assumptions. OUC Stanton currently operates at 205 ppm (@3% oxygen) inlet to the SCR and 110 ppm (@ 3% oxygen) outlet of the SCR, and these NOx values were assumed for the period for the two predicted curves and as the design basis. Inlet and outlet NOx will have a significant impact on both predicted and actual ammonia slip, and it is uncertain if the inlet and outlet NOx levels at the time of the ammonia wet chemistry measurements precisely matched the assumed inlet and outlet NOx levels used for these modeling runs. So, some small difference is reasonable to expect in light of this uncertainty. Figure 5, therefore, demonstrates that the calculated ammonia slip from CAT MANAGER™ corresponded reasonably well with the measured values.

Figure 3. OUC Stanton Unit #2 SCR Reactor (Ref. 2)

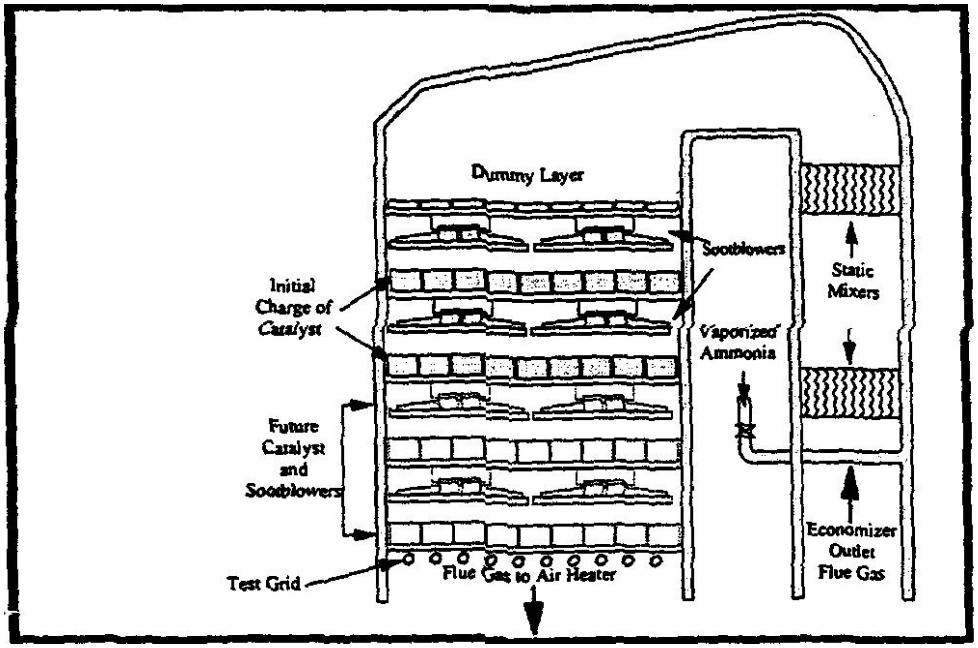


Figure 4. OUC Stanton #2 Original Catalyst Management Plant (Ref. 2)

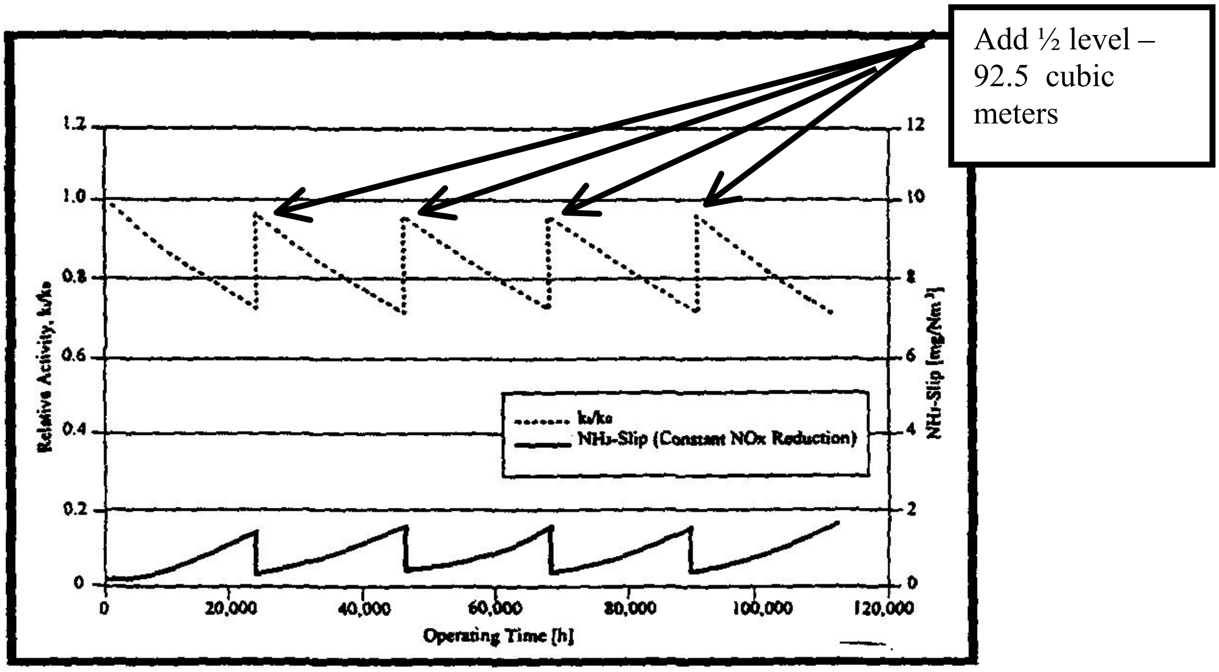
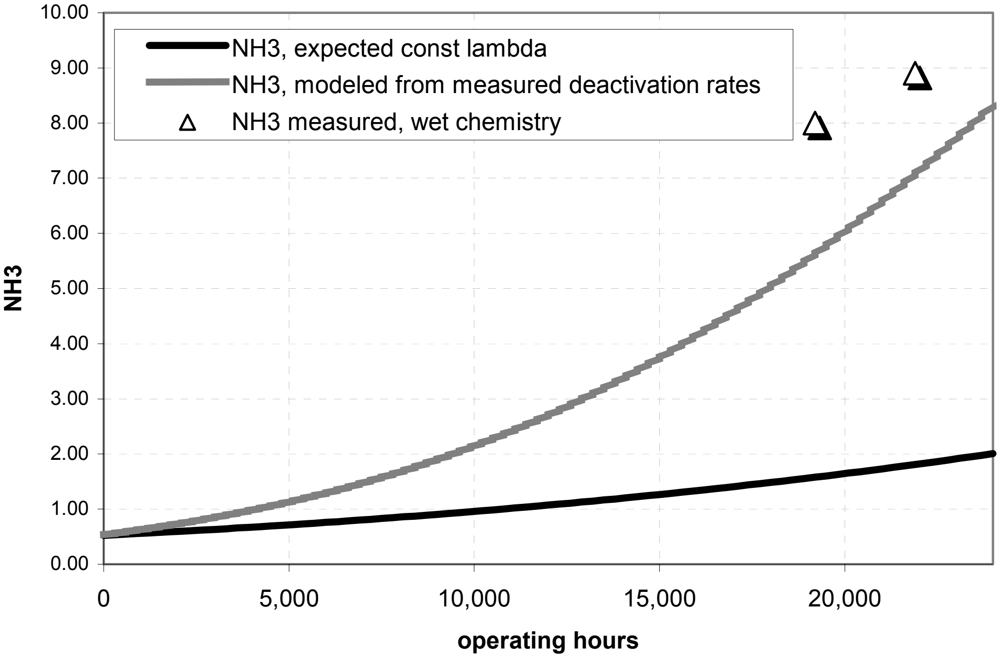

Add ½ level – 92.5 cubic meters

Figure 5. NH3 for OUC
measured with wet chemistry and modeled with CAT MANAGER(tm)



In order to maintain a three-year period between catalyst changing events while preserving acceptable boiler and SCR performance, OUC, with input from the catalyst supplier, modified their catalyst management plan to allow up to 4 ppm of ammonia slip and increased catalyst loading. In April of 1999 OUC added a full level of catalyst to Level 3. In April 2002, three years after filling level 3 with 185 cubic meters of catalyst, OUC filled Level 4 with 231 cubic meters of catalyst. The change in volume was due to a new standard element height from the manufacturer. At this point it is important to reiterate that the decisions made so far regarding catalyst management at OUC were made without the use of CAT MANAGER™ and were based upon the analysis of the catalyst supplier and OUC. OUC has not yet determined if levels 1 through 3 will be replaced with 185 cubic meters of catalyst, 231 cubic meters of catalyst or whether another approach will be used. Catalyst activity information from the April 2002 catalyst samples, which corresponds to 47,294 operating hours on levels 1 and 2, 23,614 operating hours on Level 3 and 0 hours on newly-installed Level 4, were used to establish initial conditions for modeling future SCR management strategies. Assumptions were also made about future catalyst deactivation and SCR operation. With this information, modeling with CAT MANAGER™ made the projections of performance in Figure 6a. Two scenarios are shown in Figure 6a. In one scenario, existing levels are replaced with 231 m^3 of new catalyst. In this case ammonia slip is projected to stay well below 4 ppm. In another scenario, existing levels are replaced with 185 m^3 of new catalyst. Of course, how accurately these models predict future performance will be determined in large part by how closely future deactivation rates match the assumed rates in the model and how closely assumed operating conditions match actual operating conditions. Therefore, annual catalyst activity measurements and monitoring of operation is important, and projections should be revised as new information on catalyst deactivation is gained or operating conditions change.

From Figure 6a it appears that it may not be necessary to replace as much as 231 cubic meters of catalyst every three years in order to maintain a 4 ppm ammonia slip limit. Figure 6a also shows that addition of 185 cubic meters should be adequate for maintaining below 4 ppm slip for several years (about 11) but may not be adequate for maintaining below 4 ppm of ammonia slip thereafter. Figure 6b compares the cumulative catalyst consumption of changing 231 cubic meters every three years to that of replacing 185 cubic meters of catalyst every three years. As expected, replacing 185 cubic meters results in significantly less catalyst usage over the evaluation period. Based upon these modeling results, OUC may be able to meet their three-year period between catalyst changes while maintaining under 4 ppm slip while adding less than 231 m^3 of catalyst during catalyst replacement.

Modeling Regeneration of Catalyst

Regeneration of catalyst through mechanical cleaning and sometimes through chemical cleaning and addition of active component is a potentially cost saving approach to catalyst management. As noted earlier, this approach involves a very different order of catalyst removal/replacement events. CAT MANAGER™ version 2.0 will model this approach as well as traditional add-and-replace or add-and-regenerate approaches that fill the SCR reactor and then keep the SCR reactor full.[1] For the purpose of evaluating regeneration of catalyst we evaluated multiple regeneration scenarios. In these cases, instead of filling the SCR reactor in April 2002, at that point a regeneration program was commenced where two layers (one level or two half levels) were maintained empty at any time. Spent catalyst would be removed for regeneration and regenerated catalyst would be put into the empty levels once the limit of 4 ppm slip was reached. Alternatively, in CAT MANAGER™ we could have set specific time periods for catalyst changing events (as was done for the modeling of Figures 6a and 6b) rather than reaching an ammonia slip limit. However, we wanted to estimate the maximum period between (or, minimum frequency of) catalyst changing events. Figure 7a shows the ammonia slip and k/ko predictions and Figure 7b shows cumulative catalyst usage predictions for two different regeneration simulations where catalyst was regenerated to 100% of the original activity of the catalyst when it was new. In one simulation a full level of 185 m^3 is removed and 185 m^3 of regenerated catalyst is installed in an already empty level. In the other case one half level (one layer of 92.5 m^3) is removed and a regenerated layer is installed in an empty layer. As shown in Figure 7a and b, more catalyst changing events are necessary if pursuing a regeneration approach than if replacing spent catalyst with new catalyst. However, regenerating a half level at a time reduces the catalyst usage somewhat. Therefore, the increased cost of more frequent, but shorter, outages should be compared to the savings in catalyst regeneration costs.

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[1] CAT MANAGER version 1.0 models add-and-replace or add-and-regenerate, but not the type of regeneration approaches that have recently been introduced.

Figure 6a. Replace Projection for OUC

modeled with CAT MANAGER(tm)

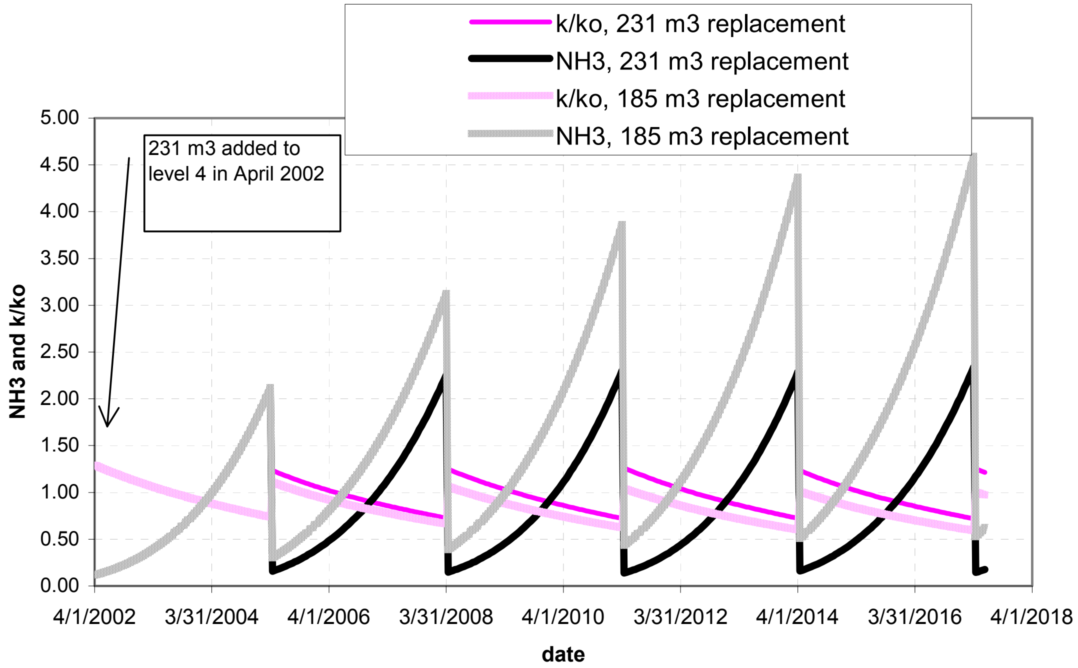
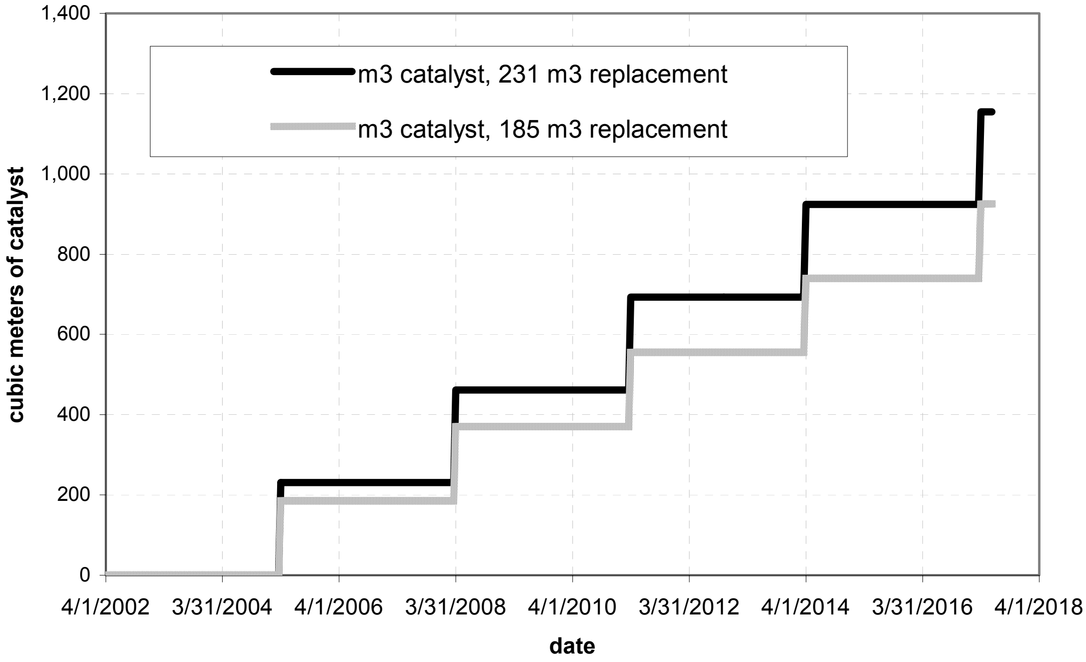


Figure 6b. Replace Projection for OUC

modeled with CAT MANAGER(tm)



While it was assumed for the simulations of Figures 7a and 7b that the regenerated catalyst has the same activity and deactivation characteristics as new catalyst, in reality activity and deactivation rates of regenerated catalyst may differ from new catalyst and such circumstances can be modeled with CAT MANAGER™. Figures 8a and 8b compare regeneration to 100% of the activity of new catalyst with regeneration to 95% of the activity of new catalyst. As shown, an additional catalyst regeneration event is necessary over the evaluated period if catalyst activity is decreased to 95% from 100%.

As noted earlier, a regeneration procedure may entail a much more complex sequencing of catalyst additions and replacements. CAT MANAGER™ will make projections of catalyst addition and removal and show graphically, and in tables when, where, and how much catalyst is projected to be added and removed. As an example, Figure 9 shows the catalyst addition and removal sequence for the 95% regeneration case shown in Figures 8a and b.

From Figures 6a through 8b, it is shown for the case of OUC Stanton #2 that regeneration is expected to entail somewhat more frequent catalyst changing and affects a higher quantity of catalyst than replacement of new catalyst. This is because of the higher volume of catalyst that is maintained in the SCR when replacing with new and the resulting longer interval period between catalyst changing events. However, if the cost of regenerating catalyst is significantly less than the cost of the same volume of new catalyst, the increased cost of more frequent catalyst changes associated with regeneration could be overcome. The potentially higher cost of more frequent catalyst changing events will also be offset somewhat by lower parasitic power losses. Therefore, when making a decision to regenerate or not, it is necessary to consider all of these effects. With CAT MANAGER™, all of these costs are modeled, detailed cash flow projections are made and displayed graphically and in tabular form, and the present value of each of these costs is estimated.

Figure 7a. 100% Regeneration Projection for OUC

modeled with CAT MANAGER(tm)

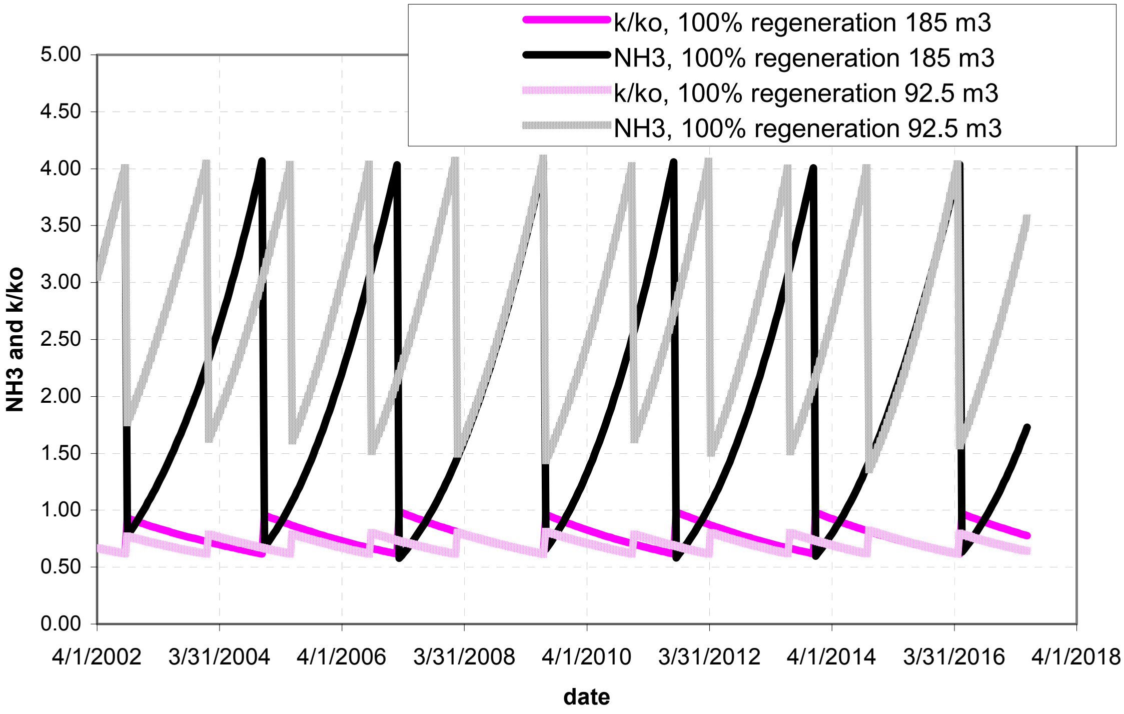


Figure 7b. 100% Regeneration Projection for OUC

modeled with CAT MANAGER(tm)

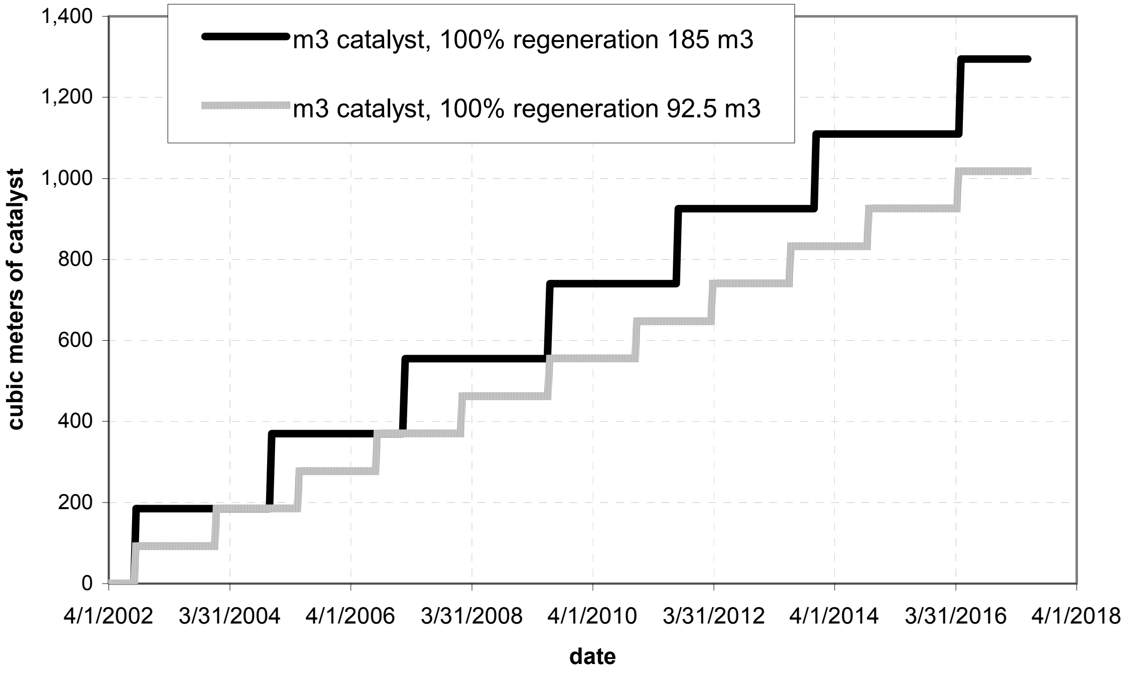


Figure 8a. 100% and 95% Regeneration Projection for OUC

modeled with CAT MANAGER(tm)

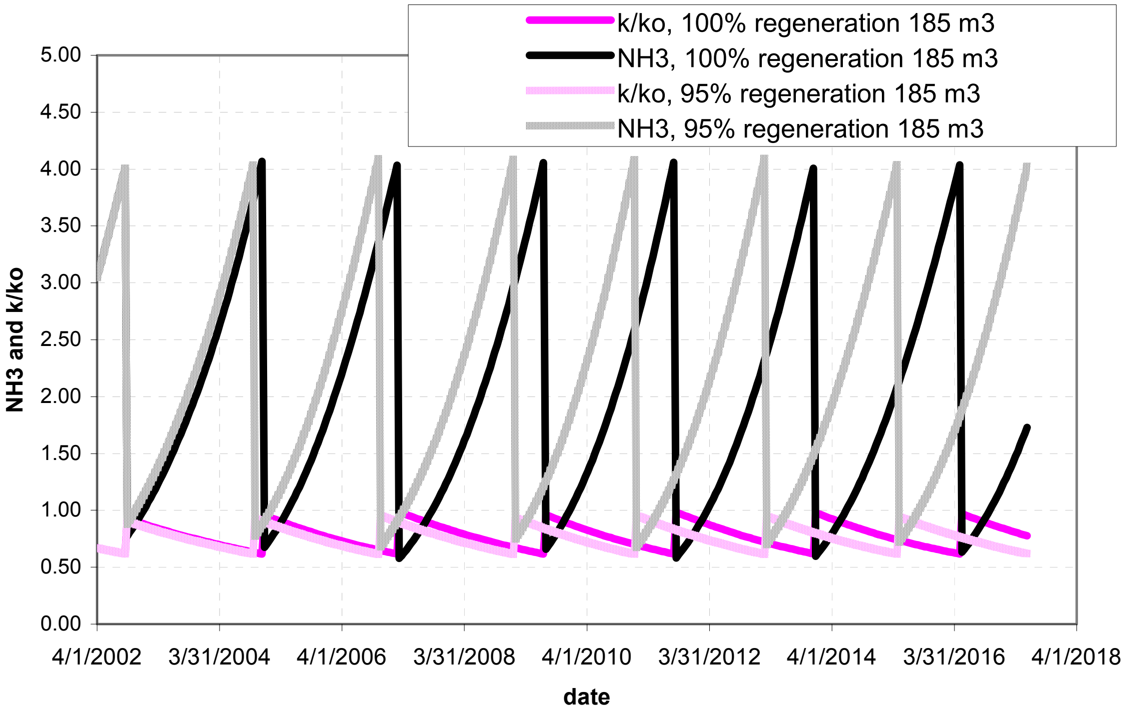


Figure 8b. 100% and 95% Regeneration Projection for OUC

modeled with CAT MANAGER(tm)

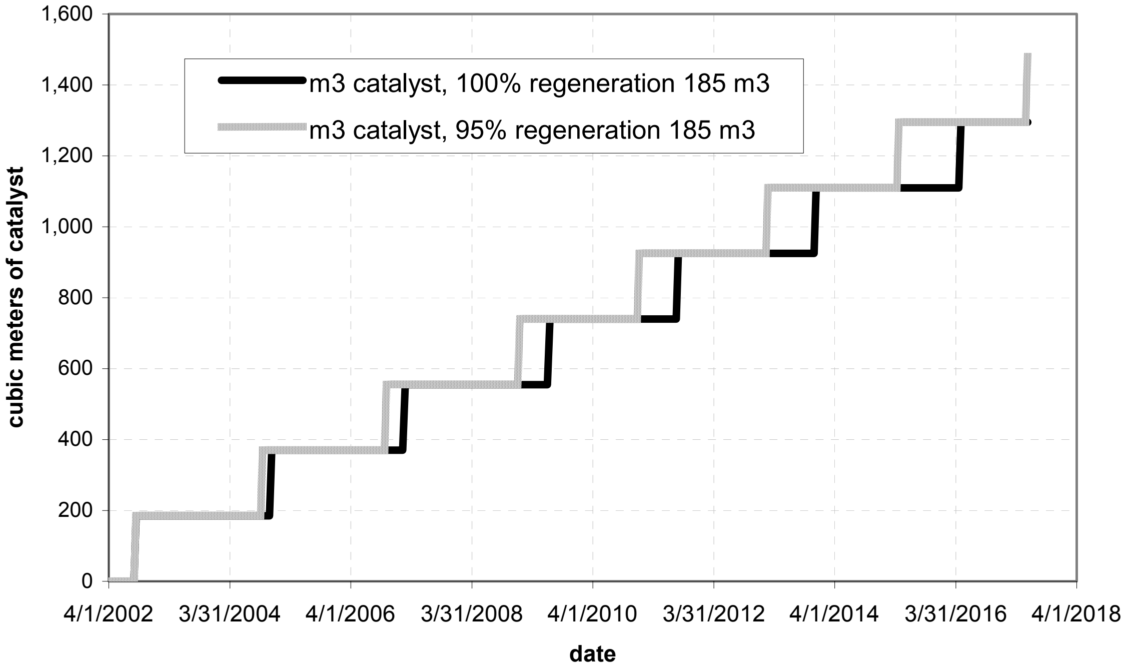
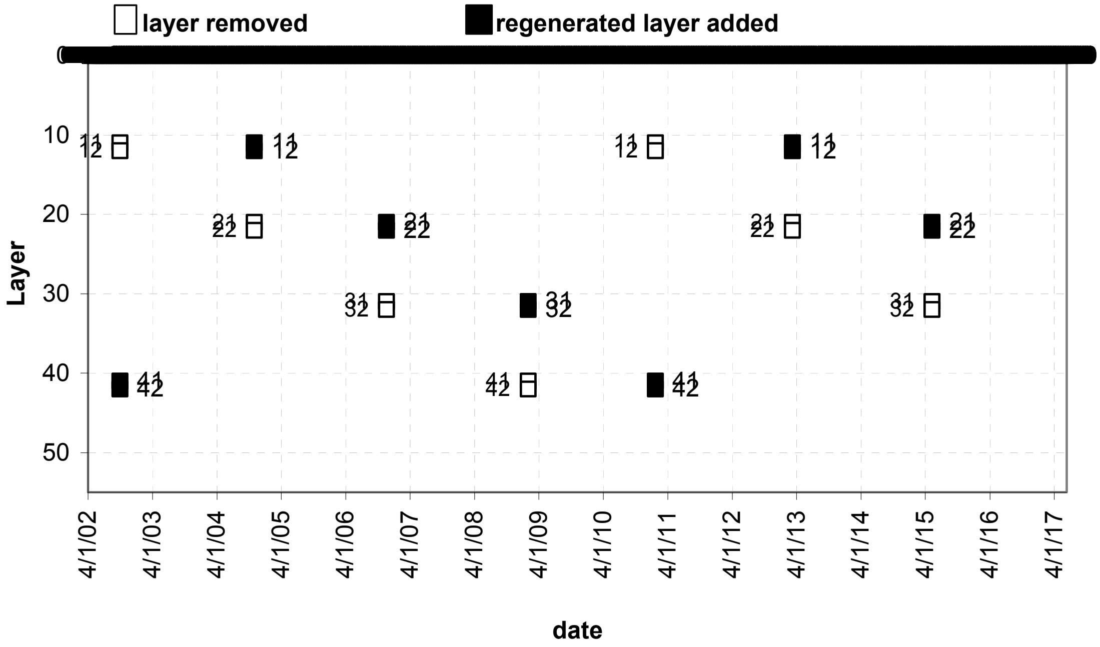


Figure 9. Regenerated Layers
use only for regeneration strategies



CONCLUSIONS

In this paper we described some features of a software tool that can help operators make decisions regarding catalyst management. In this paper we also discussed how at OUC Stanton it was necessary to modify the catalyst management plan because actual operating conditions and catalyst behavior were not as originally planned. Projections of possible future catalyst management scenarios were made with a software tool that was developed for this purpose. The following are key points in the paper.

- Catalyst management involves optimizing a wide range of parameters, in addition to catalyst usage. Having a software tool to quickly evaluate different scenarios is very useful. The paper discussed several important features that such a tool should possess.

- Because of the many factors to consider, the most cost-effective catalyst management approach may not be the one that results in the lowest amount of catalyst usage or amount of catalyst regeneration over the period. Other factors, such as the cost of lost production during outages, cost of parasitic power and other effects need to be considered.

- In some cases operating conditions and catalyst behavior will differ somewhat from the actual predictions and it will then be necessary to reevaluate catalyst management options. This is what happened at OUC Stanton. In these situations a tool for evaluating future scenarios for catalyst management based upon the new information is very useful for SCR operators.

- A catalyst management tool that is licensed by OUC and others was benchmarked against actual data and provided reasonable correspondence with measured performance.

- Modeling of possible future catalyst management scenarios for OUC Stanton was performed. Scenarios that were assessed included future replacement of catalyst, future regeneration of catalyst, and variations of these approaches. CAT MANAGER™ version 2 provided valuable insights to the trade-offs between approaches and made analysis faster, easier and interactive.

- Regular measurement of catalyst activity provides important information for the model and will enhance predictive capability of the model. Thus, having such a model is not a substitute for a regular catalyst testing. The model and the testing program enhance one another - with the testing providing useful information for the model and the model using that information as input for testing possible future scenarios.

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