

WHEN YOU NEED TO BE SURE

SGS

CyFlex® Knowledge Article

Diesel Exhaust Fuel (DEF) Metering

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Summary

This document describes the scheme used to control urea dosing to the SCR portion of the test cell abatement systems used at STC. The first section describes the properties of urea and the reactions that are used to reduce NO_x. The characteristics of the SCR are described in the next section followed by development of the equations describing the ideal dosing rate required to achieve a target NO_x conversion efficiency.

These equations are then further developed for use as feedforward, error scaling and integral bounding terms for closed loop control of NO_x conversion efficiency. The metering rate target provided by this outer control loop is used as input to an inner control loop that controls the flow from two urea metering pumps.

Refer to the following:

- [Abatement Control diagram](#) that illustrates this entire control scheme
- [Urea Metering Control Experiments](#) for description of a series of experiments that were performed while developing closed loop control of metering

DEF Properties

The properties of Diesel Exhaust Fluid (DEF) or 32.5% Automotive Grade Urea Solution (AUS 32) are defined in ISO 22241, which replaces the original DIN 70070. Refer to the following:

- <https://static.webshopapp.com/shops/021124/files/053436992/msds-adblue-aus-32.pdf>
- https://en.wikipedia.org/wiki/Diesel_exhaust_fluid

This document states that DEF is nominally 32.5 % urea by weight with the remainder distilled water for a mass fraction $x_{DEF} = 0.325$. The urea concentration must be in the range 31.8 – 33.2 % by weight. The resulting DEF density should be in the range 1.087 – 1.093 g/cm³. If we assume that the density range corresponds to the concentration range, a 32.5% by weight DEF solution should have a density $\rho_{DEF} = 1.090 \text{ g/cm}^3$.

The Wikipedia reference above states that the important reactions in the NO_x reduction process are:

Hydrolysis reaction:



NO SCR reaction:



NO₂ SCR reaction:



Given these reactions, we can calculate the number of moles of urea required to reduce a mole of NO or NO₂, $\delta_{urea/NO}$ or δ_{urea/NO_2} using

NO SCR reaction:

$$\delta_{\text{urea/NO}} = \frac{1 \text{ mole urea}}{2 \text{ moles NH}_3} \frac{4 \text{ moles NH}_3}{4 \text{ moles NO}} = 0.5 \text{ mole urea/mole NO} \quad \text{def.4}$$

NO2 SCR reaction:

$$\delta_{\text{urea/NO}} = \frac{1 \text{ mole urea}}{2 \text{ moles NH}_3} \frac{8 \text{ moles NH}_3}{6 \text{ moles NO}_2} = 0.667 \text{ mole urea/mole NO} \quad \text{def.5}$$

If we define $\alpha = \frac{n_{\text{NO}}}{n_{\text{NO}_x}}$ as the number of moles of NO per mole of NO_x, we can calculate the number of moles of urea required to reduce a mole of NO_x, $\delta_{\text{urea/NO}_x}$, as

$$\tau_{\text{urea/NO}_x} = \alpha \tau_{\text{urea/NO}} + (1 - \alpha) \tau_{\text{urea/NO}_2} \quad \text{def.6}$$

According to: http://www.chemicalbook.com/ChemicalProductProperty_EN_CB5853861.htm

the molecular weight of urea is $M_{\text{urea}} = 60.06 \text{ g/mol}$.

Since most DEF metering devices are volumetric, we need to know the number of moles of urea per unit volume of DEF, $\lambda_{\text{urea/DEF}}$. For a 32.5 % by weight urea solution:

$$\begin{aligned} \lambda_{\text{urea/DEF}} &= x_{\text{urea/DEF}} \frac{\rho_{\text{DEF}}}{M_{\text{urea}}} \\ &= \left(\frac{0.325 \text{ g urea}}{1.0 \text{ g DEF}} \right) \left(\frac{1.090 \text{ g DEF/cm}^3}{60.06 \text{ g urea/mol}} \right) \\ &= 0.005898 \text{ mol urea/cm}^3 \text{ DEF} \\ &= 5.898 \text{ mol urea/liter DEF} \end{aligned} \quad \text{def.7}$$

We can combine the previous equations to calculate the volume of urea required to convert a mole of NO_x, as

$$\phi_{\text{DEF/NO}_x} = \frac{\tau_{\text{urea/NO}_x}}{\lambda_{\text{urea/DEF}}} = \frac{\alpha \tau_{\text{urea/NO}} + (1 - \alpha) \tau_{\text{urea/NO}_2}}{\lambda_{\text{urea/DEF}}} \quad \text{def.8}$$

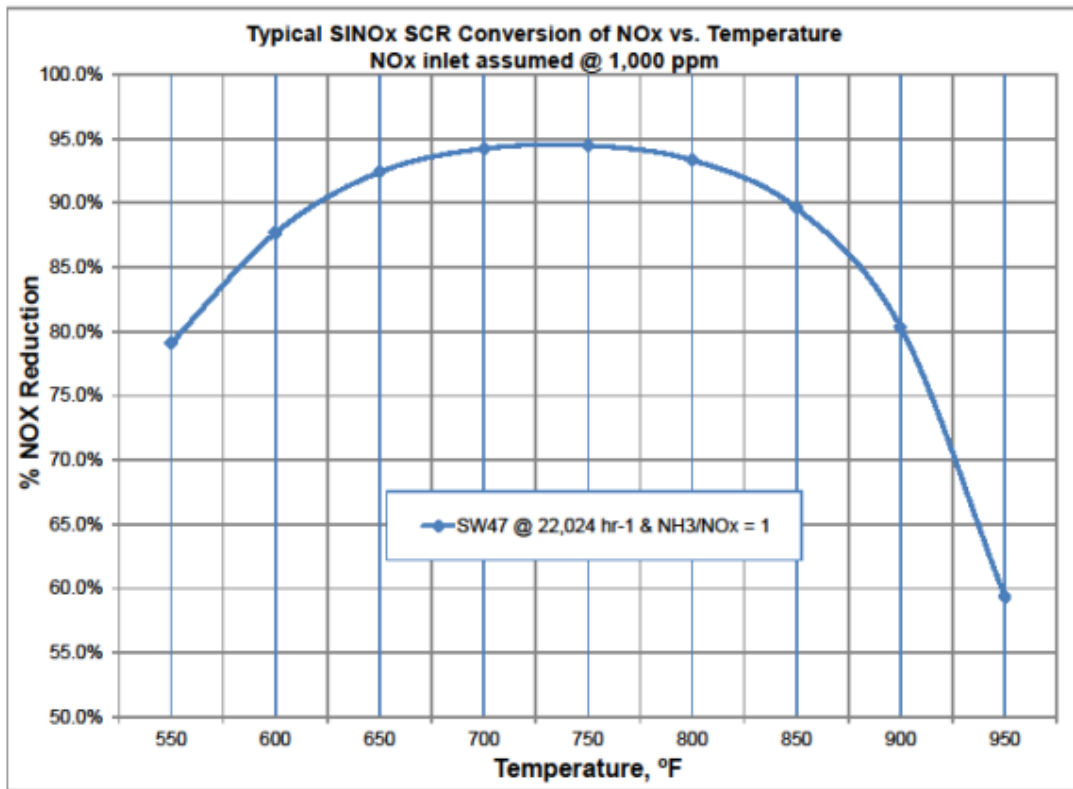
NOx Conversion Efficiency

The NOx conversion efficiency of the SCR, η_{NOx} , is defined as

$$\eta_{NOx} = \frac{y_{NOx,in} - y_{NOx,out}}{y_{NOx,in}} \quad \text{def.9}$$

where $y_{NOx,in}$ is the NOx concentration entering the catalyst and $y_{NOx,out}$ is the concentration at the catalyst exit.

The manufacturer of the SINOx catalyst has provided the theoretical curve of conversion efficiency vs temperature shown below.



The actual conversion efficiency, $\eta_{NOx,theor}$, will have to be measured experimentally and correlated with the temperatures measured before and after the catalyst. Servotech came up with the following set of equations that appear to be based on a combination of the manufacturer supplied data and their observations.

$$T_{avg} = \frac{(T_{cat,in} + T_{cat,out})}{2} \quad \text{def.10}$$

If T_{avg} is less than 951F and greater than or equal to 580F, then

$$\eta_{NOx,theor} = -6.69226e-9 \times T_{avg}^4 + 1.82549e-5 \times T_{avg}^3 - 1.87659e-2 \times T_{avg}^2 + 8.64210 \times T_{avg} - 1.41502e3 \quad \text{def.11}$$

or if T_{avg} is less than 528F and greater than or equal to 513F, then

$$\eta_{NOx,theor} = -3.43910e-4 \times T_{avg}^2 + 4.725736e-1 \times T_{avg} - 69.42777 \quad \text{def.12}$$

or if T_{avg} is less than 513F and greater than or equal to 257F, then

$$\eta_{NOx,theor} = -3.31358e-8 \times T_{avg}^4 + 4.65272e-5 \times T_{avg}^3 - 2.32571e-2 \times T_{avg}^2 + 5.11897 \times T_{avg} - 4.09512e2 \quad \text{def.13}$$

else if T_{avg} is less than 257F or greater than or equal to 951F, then

$$\eta_{NOx,theor} = 0 \quad \text{def.14}$$

The NOx efficiency curve should be viewed as the practical maximum capability of the catalyst across the engine operating range. It might be possible to get slightly higher conversion efficiency at some exhaust flow rates and NOx concentrations, but only at the risk of overdosing urea.

The catalyst will act as a sponge and absorb excess ammonia up to a point, but eventually it will begin to slip ammonia into the exhaust stream. Typical NOx sensors used for closed loop dosing control respond to ammonia and report it as NOx. The resulting apparent low conversion would result in additional overdosing if the problem is not detected.

It is therefore desirable to target a NOx conversion efficiency, $\eta_{NOx,tar}$, that is slightly lower than the maximum across the operating range by applying a multiplier, κ_{mult} . So

$$\eta_{NOx,tar} = \kappa_{mult} \eta_{NOx,theor} \quad \text{def.15}$$

Theoretical DEF Dosing Quantity

The molar conversion rate of NOx, $\dot{n}_{NOx,conv}$, is given by

$$\dot{n}_{NOx,conv} = \frac{\dot{m}_{exh}}{M_{exh}} (y_{NOx,in} - y_{NOx,out}) \tag{def.16}$$

where \dot{m}_{exh} is the exhaust mass flow rate and M_{exh} is the exhaust molar mass.

Introducing the conversion efficiency gives us

$$\dot{n}_{NOx,conv} = \frac{\dot{m}_{exh}}{M_{exh}} y_{NOx,in} \frac{(y_{NOx,in} - y_{NOx,out})}{y_{NOx,in}} = \frac{\dot{m}_{exh}}{M_{exh}} y_{NOx,in} \eta_{NOx} \tag{def.17}$$

The required volume flow rate of DEF, \dot{V}_{DEF} , that would have to be metered into the SCR to achieve this efficiency would be given by

$$\dot{V}_{DEF} = \frac{\dot{m}_{exh}}{M_{exh}} y_{NOx,in} \eta_{NOx} \phi_{DEF/NOx} \tag{def.18}$$

Combining previous equations gives us

$$\dot{V}_{DEF} = \frac{\dot{m}_{exh}}{M_{exh}} y_{NOx,in} \kappa_{mult} \eta_{NOx,theor} \frac{\alpha \tau_{urea/NO} + (1-\alpha) \tau_{urea/NO_2}}{\lambda_{urea/DEF}} \tag{def.19}$$

Or in terms of a NOx efficiency target

$$\dot{V}_{DEF} = \frac{\dot{m}_{exh}}{M_{exh}} y_{NOx,in} \eta_{NOx,tar} \frac{\alpha \tau_{urea/NO} + (1-\alpha) \tau_{urea/NO_2}}{\lambda_{urea/DEF}}$$

Open Loop or
Feedforward
Term def.20

Practical Dosing Control

To apply the previous equation to control dosing, we need to know the mass flow rate of exhaust, the NOx concentration entering the catalyst, and the catalyst temperature. We also need to specify an efficiency multiplier and at least guess at the ratio of moles of NO per mole of NOx. We do not need to know the resulting exit NOx concentration to do open loop control.

If we do have a way of measuring exit NOx concentration, we can still apply the above equations as a feedforward term in a closed loop control scheme. Even if we make the most conservative

assumption that all the NOx is NO, we would only expect the feedforward term to be low by one sixth.

For PID control of NOx efficiency, it is useful to know the sensitivity of the controller output to the controller feedback since this is a rough estimate of the required proportional gain. Ideally, this would be a nearly constant value. Taking the partial derivative of the urea dosing rate with respect to the target efficiency gives us

$\frac{\delta \dot{V}_{DEF}}{\delta \eta_{NOx,tar}} = \frac{\dot{m}_{exh}}{M_{exh}} y_{NOx,in} \frac{\alpha \tau_{urea/NO} + (1-\alpha) \tau_{urea/NO_2}}{\lambda_{urea/DEF}}$	Error Scaling Term	def.21
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This is far from a constant value. The exhaust mass flow rate alone can vary greatly across the engine operating range. Fortunately, the CyFlex control task allows us to specify an error scaling term. The above equation defines that term.

We still have the problem of not accurately knowing α , the ratio of moles of NO per mole of NOx. This is effectively an integral term that must be created or destroyed as the ratio changes. We can bound the upper end of the dosing range by assuming all the NOx is NO2 to give us

$$\dot{V}_{DEF,upper} = \frac{\dot{m}_{exh}}{M_{exh}} y_{NOx,in} \eta_{NOx,tar} \frac{\tau_{urea/NO_2}}{\lambda_{urea/DEF}} \tag{def.22}$$

The lower end is defined by

$$\dot{V}_{DEF,lower} = \frac{\dot{m}_{exh}}{M_{exh}} y_{NOx,in} \eta_{NOx,theor} \frac{\tau_{urea/NO}}{\lambda_{urea/DEF}} \tag{def.23}$$

So we can impose an upper integral bound that is the difference between the current feedforward term and the upper dosing limit

$$\Delta \dot{V}_{DEF,upper} = \frac{\dot{m}_{exh}}{M_{exh}} y_{NOx,in} \eta_{NOx,tar} \left(\frac{\tau_{urea/NO_2}}{\lambda_{urea/DEF}} - \frac{\alpha \tau_{urea/NO} + (1-\alpha) \tau_{urea/NO_2}}{\lambda_{urea/DEF}} \right) \tag{def.24}$$

or

$\Delta \dot{V}_{DEF,upper} = \frac{\dot{m}_{exh}}{M_{exh}} y_{NOx,in} \eta_{NOx,tar} \frac{\alpha (\tau_{urea/NO_2} - \tau_{urea/NO})}{\lambda_{urea/DEF}}$	Upper Integral Bound	def.25
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For the lower bound we get

$$\Delta \dot{V}_{DEF,upper} = \frac{\dot{m}_{exh}}{M_{exh}} y_{NOx,in} \eta_{NOx,tar} \frac{(1-\alpha)(\tau_{urea/NO} - \tau_{urea/NO_2})}{\lambda_{urea/DEF}}$$

Lower Integral
Bound def.26

The practical effect of bounding is that the integral term will be almost entirely destroyed when a sudden change is made from a high flow rate to a much lower flow rate. Given that the error scaling also goes down at the lower flow rate, it might take a very long time to eliminate an unwanted integral term if the bounding was not in place. The integral gain can be increased significantly without concern for unwanted integral windup when this scheme is used.

At this point, the output of the controller we have described is assumed to be a target DEF dosing rate. We are attempting to blend the output of two metering pumps, one large and one small, to achieve that target. A second, inner PID loop is used along with digital logic to control the pumps to achieve that goal.

When the pump command exceeds 0%, the small pump is enabled. It has to spool up rapidly to create enough pressure to exceed the popping pressure of an inline check valve which is experiencing backpressure from the atomization air supply. The small pump will deliver urea until the target flow rate hits 240 ml/min. The analog output to the small pump has been limited to not exceed that flow rate. This limit is necessary because the small flow meter located directly downstream of the small pump has an upper limit of 120% of its 200 ml/min measurement capability.

The large pump is enabled at the same flow rate. It has already been given an analog command that should be sufficient to immediately pop the check valve in its downstream line against the combined back pressure of the atomization air and urea being metered by the small pump. It will continue to supply urea all the way up to 100% of its capacity.

The combination of check valves and the flow limitations of the meters being used to supply feedback make this a less than robust control scheme. The large pump has to be enabled at the last minute to prevent it from overheating when deadheaded against the check valve at low flow rates. The check valves themselves are prone to leaking and may let air back through the system to bubble up through the urea head tank. This also makes it necessary to re-prime the metering pumps so they can build enough pressure to force all the air out of the system. Refilling the line all the way up to the lance on the roof can take considerable time if the dosing rate is constrained.

NOx Efficiency Uncertainty Calculations

The previous calculations all assume that we can accurately measure NOx concentration. But there are known limits to NOx sensor accuracy that we cannot ignore. We need to understand the uncertainty in the NOx efficiency calculations to better understand the potential impact.

The sensitivity of the NOx efficiency calculation to each of the concentration measurements is given by

$$\frac{\delta \eta_{NOx}}{\delta y_{NOx,in}} = \frac{y_{NOx,out}}{(y_{NOx,in})^2} \quad \text{def.27}$$

and

$$\frac{\delta \eta_{NOx}}{\delta y_{NOx,out}} = - \frac{1}{y_{NOx,in}} \tag{def.28}$$

We can approximate the uncertainty in the NOx concentration measurement by referring to the Cummins specification for item number 4327137. The sensor response is dependent on the fraction of NO vs NO2. The sensor is calibrated using NO, so the response is assumed to be 100%. But for NO2, the response will be only 80% of the true value. The sensor is only thought to be accurate to ± 50% for concentrations in the range of 1500 – 3000 ppm. From 100 – 1500 ppm, the stated accuracy is ± 10% at best and from 0 – 100 ppm is ± 10 ppm.

Ignoring concentrations greater than 1500 ppm, the uncertainty in the NOx concentration measurements is a function of the concentration and we can write

$$\begin{aligned} u_{y_{NOx,in}} &= \pm 10 \text{ ppm if } y_{NOx,in} \leq 100 \text{ ppm} \\ &= \pm (0.1)y_{NOx,in} \text{ if } y_{NOx,in} > 100 \text{ ppm} \end{aligned} \tag{def.29}$$

And the NOx concentration measurement is also a function of both the ratio of NO to NOx and the diminished response of the sensor to NO2. So we can write

$$y_{NOx,mea} = y_{NO} + 0.8y_{NO_2} = \alpha y_{NOx,act} + 0.8(1 - \alpha)y_{NOx,act} = (0.8 + 0.2\alpha)y_{NOx,act} \tag{def.30}$$

The sensitivity of measured NOx concentration to changes in the ratio of NO to NOx is then

$$\frac{\delta y_{NOx,mea}}{\delta \alpha} = 0.2 y_{NOx,act} \tag{def.31}$$

So if we ignore the fact that α is unlikely to be the same before and after the SCR, the combined uncertainty in the NOx efficiency as a function of the uncertainty in the concentration measurements and the ratio of NO to NOx is given by

$$\begin{aligned} (u_{c,\eta_{NOx}})^2 &= \left(\frac{\delta \eta_{NOx}}{\delta y_{NOx,in}} \right)^2 (u_{y_{NOx,in}})^2 + \left(\frac{\delta \eta_{NOx}}{\delta y_{NOx,out}} \right)^2 (u_{y_{NOx,out}})^2 + \\ &\quad \left(\frac{\delta \eta_{NOx}}{\delta y_{NOx,out}} \frac{\delta y_{NOx,out}}{\delta \alpha} \right)^2 (u_{\alpha})^2 + \left(\frac{\delta \eta_{NOx}}{\delta y_{NOx,in}} \frac{\delta y_{NOx,in}}{\delta \alpha} \right)^2 (u_{\alpha})^2 \end{aligned} \tag{def.32}$$

Plugging in previous equations gives us

$$\begin{aligned} (u_{c,\eta_{NOx}})^2 &= \left(\frac{y_{NOx,out}}{(y_{NOx,in})^2} \right)^2 (u_{y_{NOx,in}})^2 + \left(\frac{I}{y_{NOx,in}} \right)^2 (u_{y_{NOx,out}})^2 + \\ &\left(\frac{y_{NOx,out}}{(y_{NOx,in})^2} 0.2 y_{NOx,in} \right)^2 (u_\alpha)^2 + \left(\frac{I}{y_{NOx,in}} 0.2 y_{NOx,out} \right)^2 (u_\alpha)^2 \end{aligned} \quad \text{def.33}$$

The maximum uncertainty in the value of α is 1.0.

Dosing Uncertainty Calculations

If we define $\dot{V}_{DEF,max}$ as the maximum volume of urea solution we can inject without overdosing and $\dot{V}_{DEF,tar}$ as the target injection volume, to prevent overdosing, we need to be sure that the target volume plus the combined uncertainty for our ability to deliver exactly the target volume, $\sum_{i=1}^n \dot{V}_{DEF,uncert,i}$, stays below the maximum, or

$$\dot{V}_{DEF,tar} + \sum_{i=1}^n \dot{V}_{DEF,uncert,i} < \dot{V}_{DEF,max} \quad \text{def.34}$$

To this end, we define a NOx efficiency multiplier, β , that is the ratio of the target NOx efficiency to the maximum theoretical NOx efficiency. This also the ratio of target injection volume to the maximum injection volume. We can solve for the target injection volume to get

$$\beta = \frac{\eta_{NOx,tar}}{\eta_{NOx,max}} = \frac{\dot{V}_{DEF,tar}}{\dot{V}_{DEF,max}} \Rightarrow \dot{V}_{DEF,tar} = \beta \dot{V}_{DEF,max} \quad \text{def.35}$$

By combining the above equations, we find that to avoid over dosing, we need to use a NOx efficiency multiplier defined by

$$\beta \leq 1 - \frac{\sum_{i=1}^n \dot{V}_{DEF,uncert,i}}{\dot{V}_{DEF,max}} \quad \text{def.36}$$

From our previous development, we know that the volume flow rate of urea solution is a function of the following parameters.

$$\dot{V}_{DEF} = f(\dot{m}_{exh}, M_{exh}, y_{NOx,in}, y_{NOx,out}, \alpha, \lambda_{urea/DEF}, \tau_{urea/NO}, \tau_{urea/NO_2}) \quad \text{def.37}$$

The uncertainty attributable to any given parameter, x_i , is the uncertainty in the value of the parameter times the partial of the function with respect to that parameter, or

$$\dot{V}_{DEF,uncert,i} = \left(\frac{\delta f}{\delta x} \right) x_{uncert,i} \tag{def.38}$$

When describing the combined uncertainty, it is common practice to calculate it as the root sum squared of the individual contributors. In this case, we are more interested in examining the contribution of individual uncertainties. For the moment, we will consider only the uncertainty contributions of a subset of the input parameters: $y_{NOx,in}$, $y_{NOx,out}$, α and the uncertainty in the volume measurement itself.

Beginning with the equation

$$\dot{V}_{DEF} = \frac{\dot{m}_{exh}}{M_{exh}} (y_{NOx,in} - y_{NOx,out})_{tar} \frac{\alpha \tau_{urea/NO} + (1-\alpha) \tau_{urea/NO_2}}{\lambda_{urea/DEF}} \tag{def.39}$$

we can calculate the partial derivatives

$$\frac{\delta \dot{V}_{DEF}}{\delta y_{NOx,in}} = \frac{\dot{m}_{exh}}{M_{exh}} \frac{\alpha \tau_{urea/NO} + (1-\alpha) \tau_{urea/NO_2}}{\lambda_{urea/DEF}} \tag{def.40}$$

$$\frac{\delta \dot{V}_{DEF}}{\delta y_{NOx,out}} = - \frac{\dot{m}_{exh}}{M_{exh}} \frac{\alpha \tau_{urea/NO} + (1-\alpha) \tau_{urea/NO_2}}{\lambda_{urea/DEF}} \tag{def.41}$$

$$\frac{\delta \dot{V}_{DEF}}{\delta \alpha} = \frac{\dot{m}_{exh}}{M_{exh}} y_{NOx,in} \eta_{NOx,tar} \left(\frac{\tau_{urea/NO} - \tau_{urea/NO_2}}{\lambda_{urea/DEF}} \right) \tag{def.42}$$

Inlet NOx Concentration Uncertainty

Dividing by

$$\dot{V}_{max} = \frac{\dot{m}_{exh}}{M_{exh}} y_{NOx,in} \eta_{NOx,max} \frac{\alpha_{act} \tau_{urea/NO} + (1-\alpha_{act}) \tau_{urea/NO_2}}{\lambda_{urea/DEF}} \tag{def.43}$$

and considering the terms one at a time, the fractional uncertainty due to the inlet NOx concentration measurement is

$$\frac{\frac{\delta \dot{V}_{DEF}}{\dot{V}_{max}} \Delta y_{NOx,in,uncert}}{\delta y_{NOx,in}} = \frac{\Delta y_{NOx,in,uncert}}{(y_{NOx,in} - y_{NOx,out})_{max}} = \frac{\Delta y_{NOx,in,uncert}}{\eta_{max} y_{NOx,in}} \quad \text{def.44}$$

We can approximate the uncertainty in the NOx concentration measurement by referring to the Cummins specification for item number 4327137. The sensor response is dependent on the fraction of NO vs NO2. The sensor is calibrated using NO, so the response is assumed to be 100%. But for NO2, the response will be only 80% of the true value. The sensor is only thought to be accurate to ± 50% for concentrations in the range of 1500 – 3000 ppm. From 100 – 1500 ppm, the stated accuracy is ± 10% at best and from 0 – 100 ppm is ± 10 ppm. If we believe these numbers, the highest NOx efficiency multiplier we could comfortably use do to this factor alone would be

$$\beta_{y_{NOx,in}} \leq 1 - \frac{\Delta y_{NOx,in,uncert}}{\eta_{max} y_{NOx,in}} = 1 - \frac{0.10}{\eta_{max}} \quad \text{def.45}$$

which is certain to require a multiplier of less than 0.9. At anything below 100 ppm, things would deteriorate even further since the uncertainty is a flat 10 ppm.

Outlet NOx Concentration Uncertainty

The contribution due to the uncertainty of the sensor at the outlet is similar

$$\beta_{y_{NOx,out}} \leq 1 - \frac{\Delta y_{NOx,out,uncert}}{\eta_{max} y_{NOx,in}} \quad \text{def.46}$$

but in this case, we have the benefit of having the higher inlet concentration in the denominator, so the end effect should be somewhat less.

NO Ratio Uncertainty

The fractional uncertainty due to the fact that we don't know the ratio of moles of NO per mole of NOx, α , is given by

$$\frac{\frac{\delta \dot{V}_{DEF}}{\dot{V}_{max}} \Delta \alpha_{uncert}}{\delta \alpha} = \frac{\eta_{NOx,tar} (\tau_{urea/NO_2} - \tau_{urea/NO})}{\eta_{NOx,max} (\alpha_{act} \tau_{urea/NO} + (1 - \alpha_{act}) \tau_{urea/NO_2})} \quad \text{def.47}$$

We know that $\tau_{urea/NO}$ is less than τ_{urea/NO_2} , so if we assume that NOx is all NO, we should not overdose due to this factor alone. On the other hand, if we assume that NOx is all NO2 when it is really all NO, we get

$$\beta_{\alpha} \leq 1 - \frac{\eta_{NOx,tar}}{\eta_{NOx,max}} \frac{(\tau_{urea/NO_2} - \tau_{urea/NO})}{\tau_{urea/NO}} = 1 - \beta \frac{(\tau_{urea/NO_2} - \tau_{urea/NO})}{\tau_{urea/NO}} \quad \text{def.48}$$

Plugging in values gives us

$$\beta = 1 - \beta \frac{(2/3 - 1/2)}{1/2} \Rightarrow \beta = 0.75 \quad \text{def.49}$$

Or in other words, we would have to use a multiplier of 0.75 to prevent overdosing if we assumed that NOx was all NO2 and it turned out to be all NO. This suggests that it would be safest to make the assumption that NOx is all NO and then to allow some flexibility to go to higher dosing to reflect the reality that NOx has some amount of NO2.

This is the thought behind the current integral bound calculations except that we have not limited the upper bound to prevent over dosing.

Urea Measurement Flow Uncertainty

We also have to consider the effect of inaccuracies in the measurement of urea volume flow. In this case, there is no need for partial derivatives – the uncertainty is just \dot{V}_{uncert} . So we get

$$\beta = 1 - \frac{\dot{V}_{uncert}}{\dot{V}_{max}} \quad \text{def.50}$$

The manufacturer claims accuracy of 1% of full scale. Full scale for the small flow meter is 200 ml/min, so that translates into an accuracy of 2 ml/min. So at 20 ml/min, the multiplier would have to be 0.90 to prevent overdosing. In reality, our calibration has shown residuals that are much higher than 2 ml/min at low flow rates.

Dosing Strategy

Given the potential measurement uncertainty described in the previous section, it appears that we will always be in danger of over dosing, particularly at low NOx concentrations. We need to develop a strategy that minimizes the risk and provides a means for recovering from an over dosing condition.

To this end, it would appear to be best to assume that NOx is all NO by setting α to 1.0. This will give us some margin for error and allow a periodic integral reset to take us back to a lower dosing condition to allow the system to recover. We can also limit the upper integral term by setting the integral bound multiplier to a value less than 1.0. It would be useful to use the FTIR to make measurements at the inlet to see what a realistic value might be.

In the past, the integral reset lasted only one second. The computations have now been modified to allow an integral reset duration to be specified.

Integral Reset

An integral reset is accomplished by setting the integral bound multiplier to zero for a specified duration that is a fraction of a specified period. Both the period and duration are a function of the test cell ANR.

This feature is not being used at the time of this writing as the duration has been set to zero for all combinations of ANR.