

Characterization of Urea Thermolysis: Its Impact on SCR deNOx Catalyst

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CLEERS Workshop in SCR of
NOx with Urea/Ammonia
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PROBLEMS: (1) Deposit formation in the exhaust pipe prior to catalyst (2) Stoichiometric imbalance in urea consumption

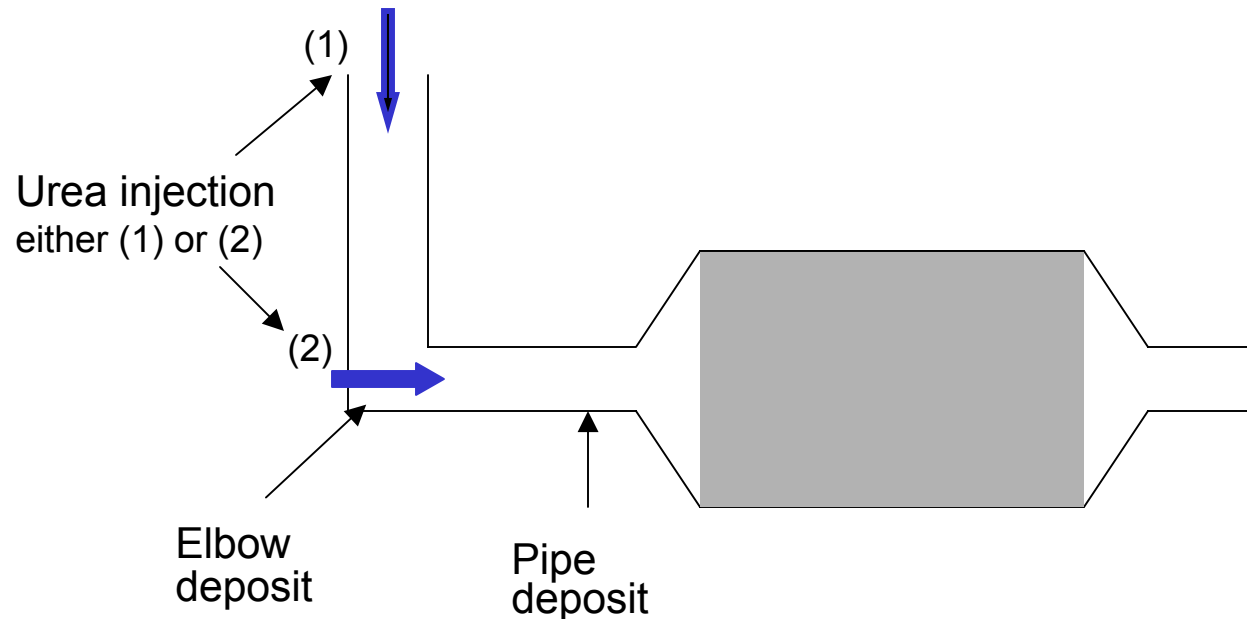
- Beige and dark brown color deposits are observed within the pipe depending upon the heating period

What are these decomposed products?

Are they responsible for excess urea consumption?

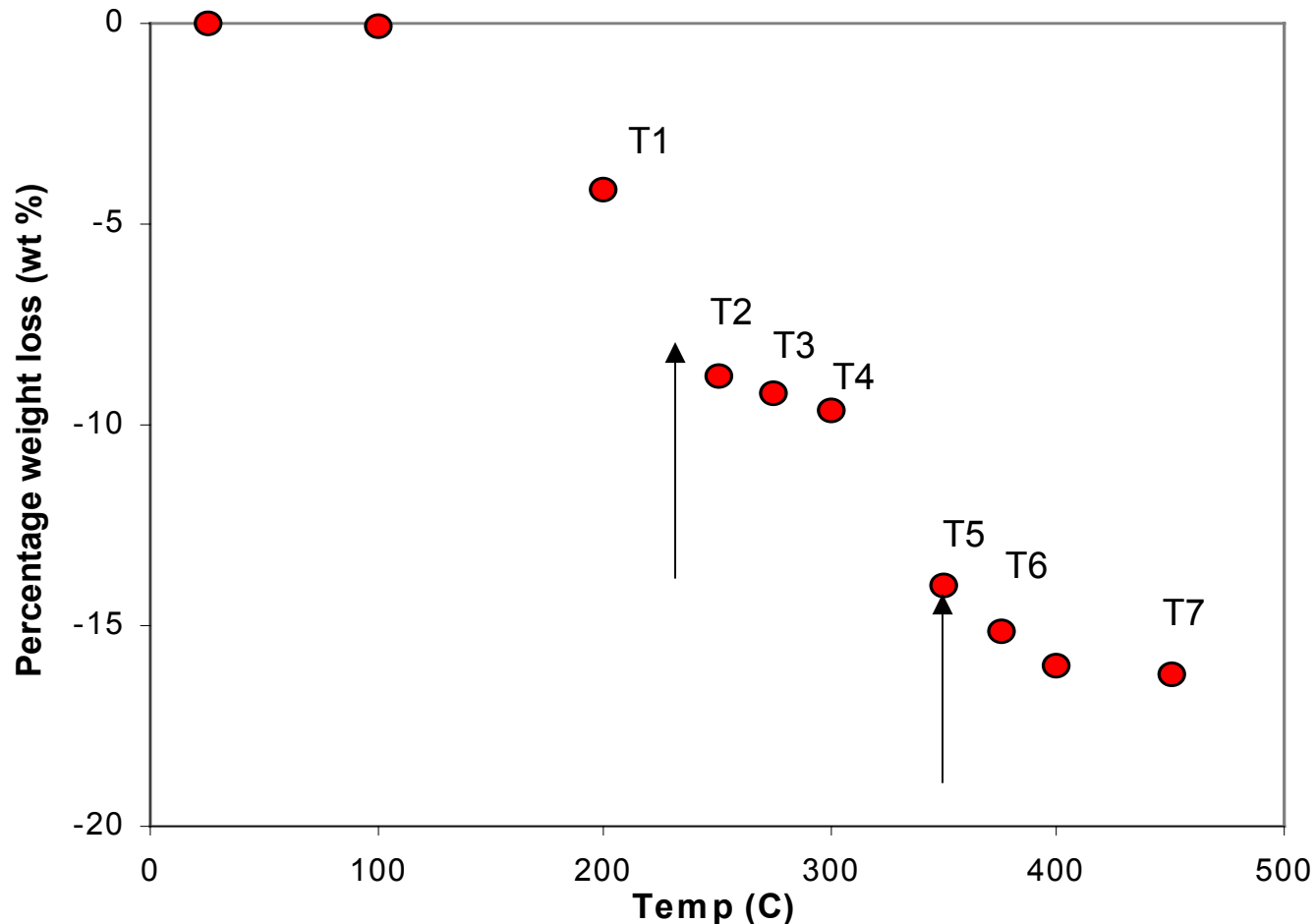
What are their impacts on catalytic performance? system design aspects?

- DRIFTS and DSC/TGA were applied to identify the decomposed components



Thermal Decomposition of Urea

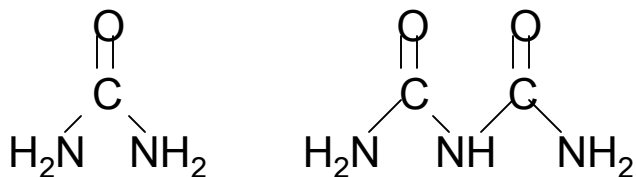
- Decomposition was conducted under stepwise mode at individual desired temperatures
- Urea thermal decomposition contains two stages:
 - (1) stage I at 220 -250°C, to form pale beige color deposit
 - (2) stage II at 340 -380°C, to form dark brown color deposit
- The final product at 450°C (T7) is a dark brown powder



Identification of Decomposed Urea Species at Various Stages Using IR

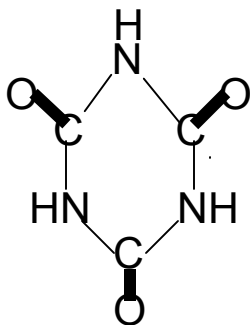
Group A:

A mixture of urea and biuret



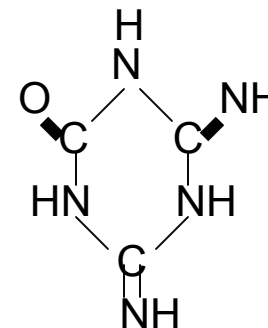
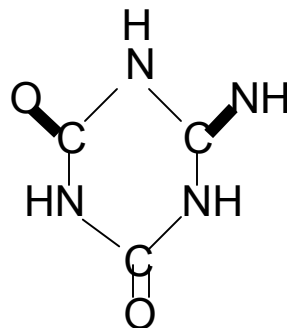
Group B:

The main component is cyanuric acid



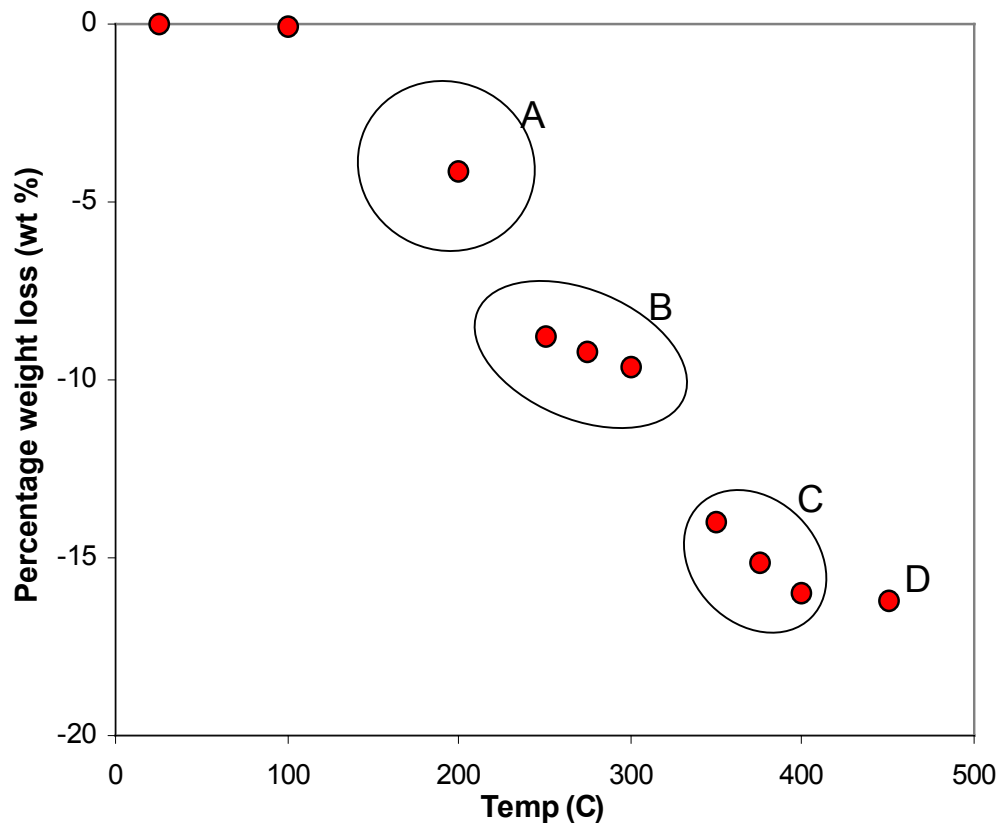
Group C:

Major components are ammeline and ammelide



Group D:

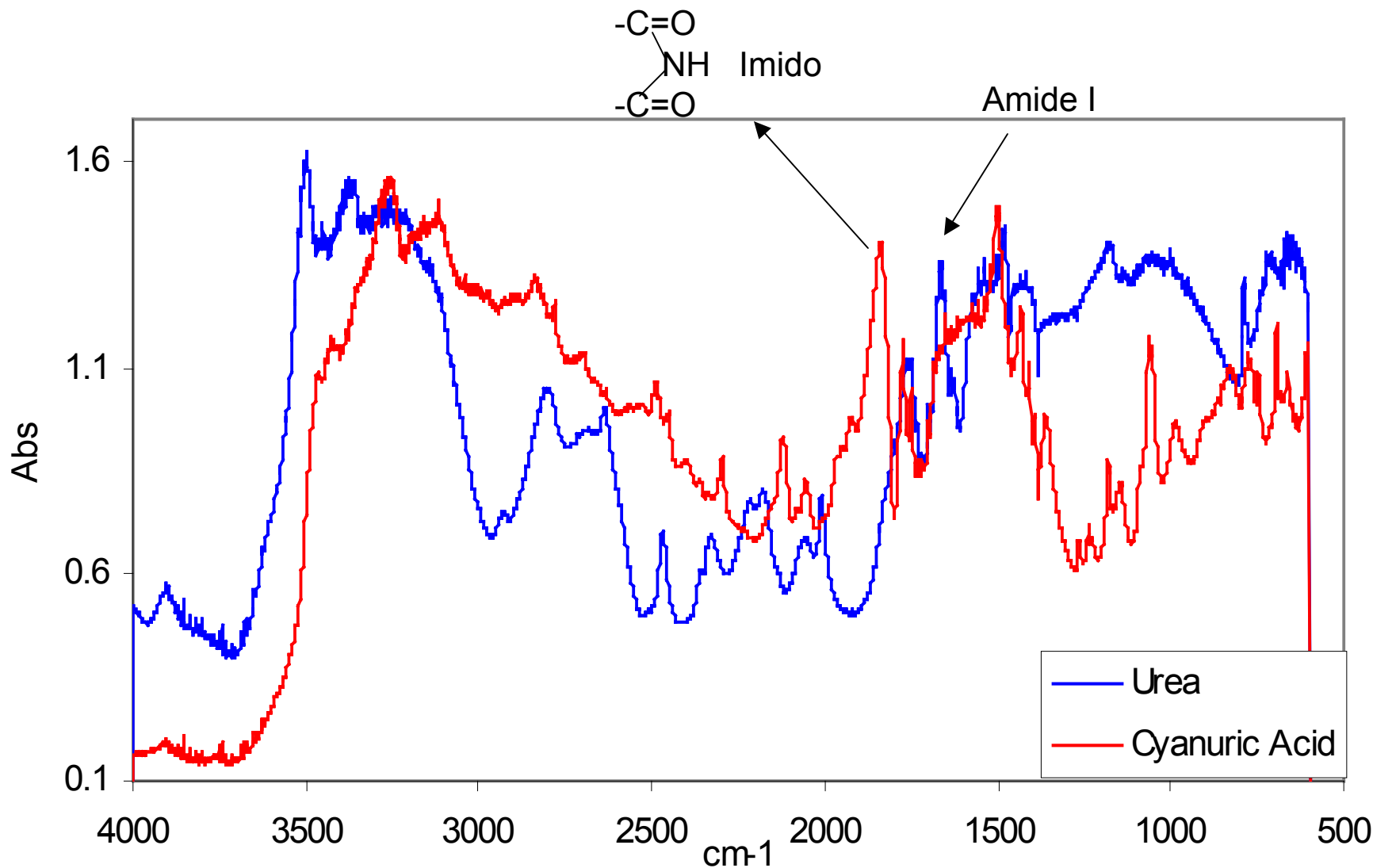
Polymeric products from group C



DRIFTS Spectra of Urea and The Decomposed Deposit at 220°C

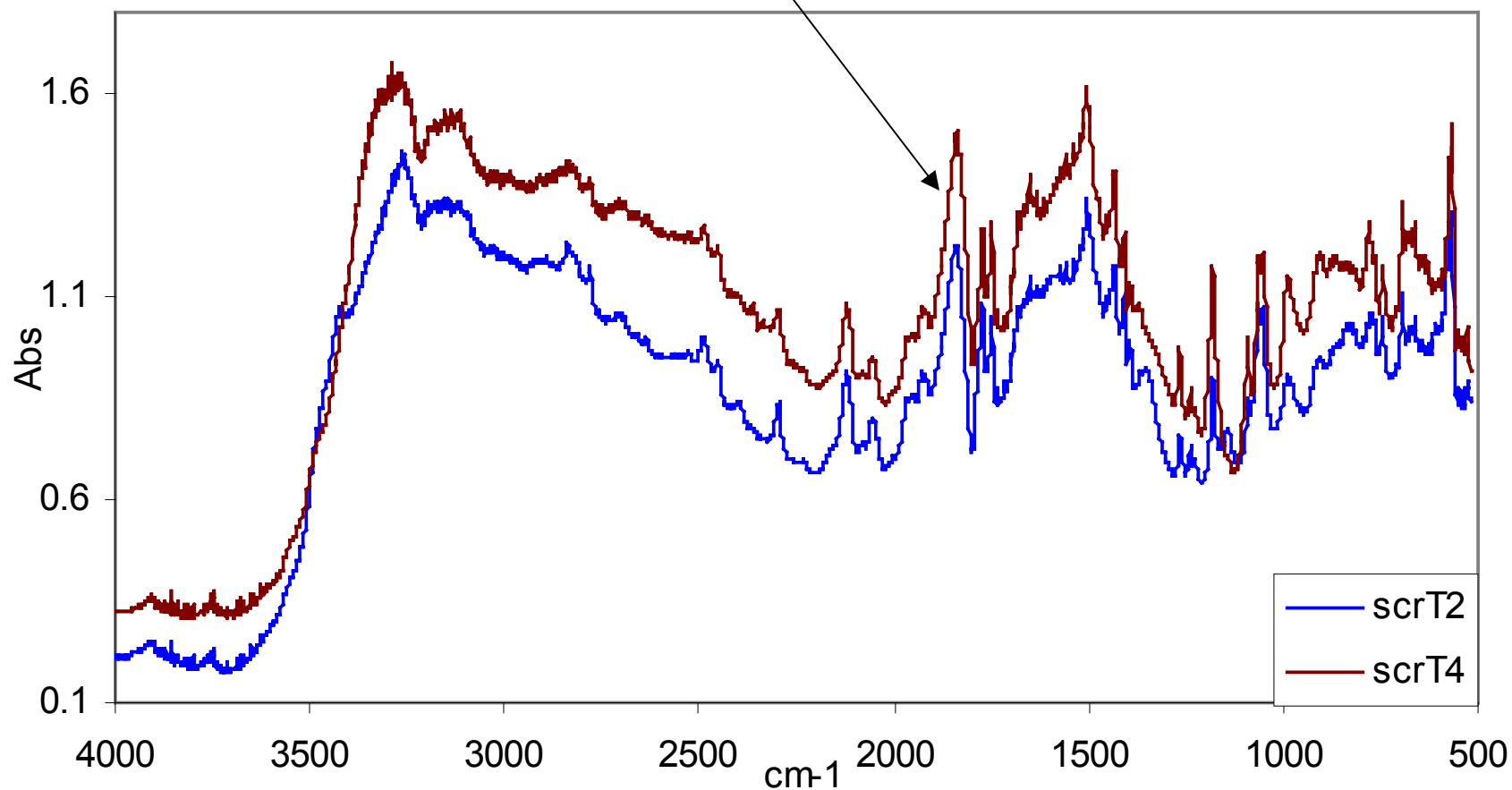
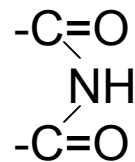
Urea powder was decomposed at 220°C to generate white cyanuric acid powder

-the disappearance of primary amide I band at 1668 cm⁻¹ and the ν_{NH} at 3500 cm⁻¹



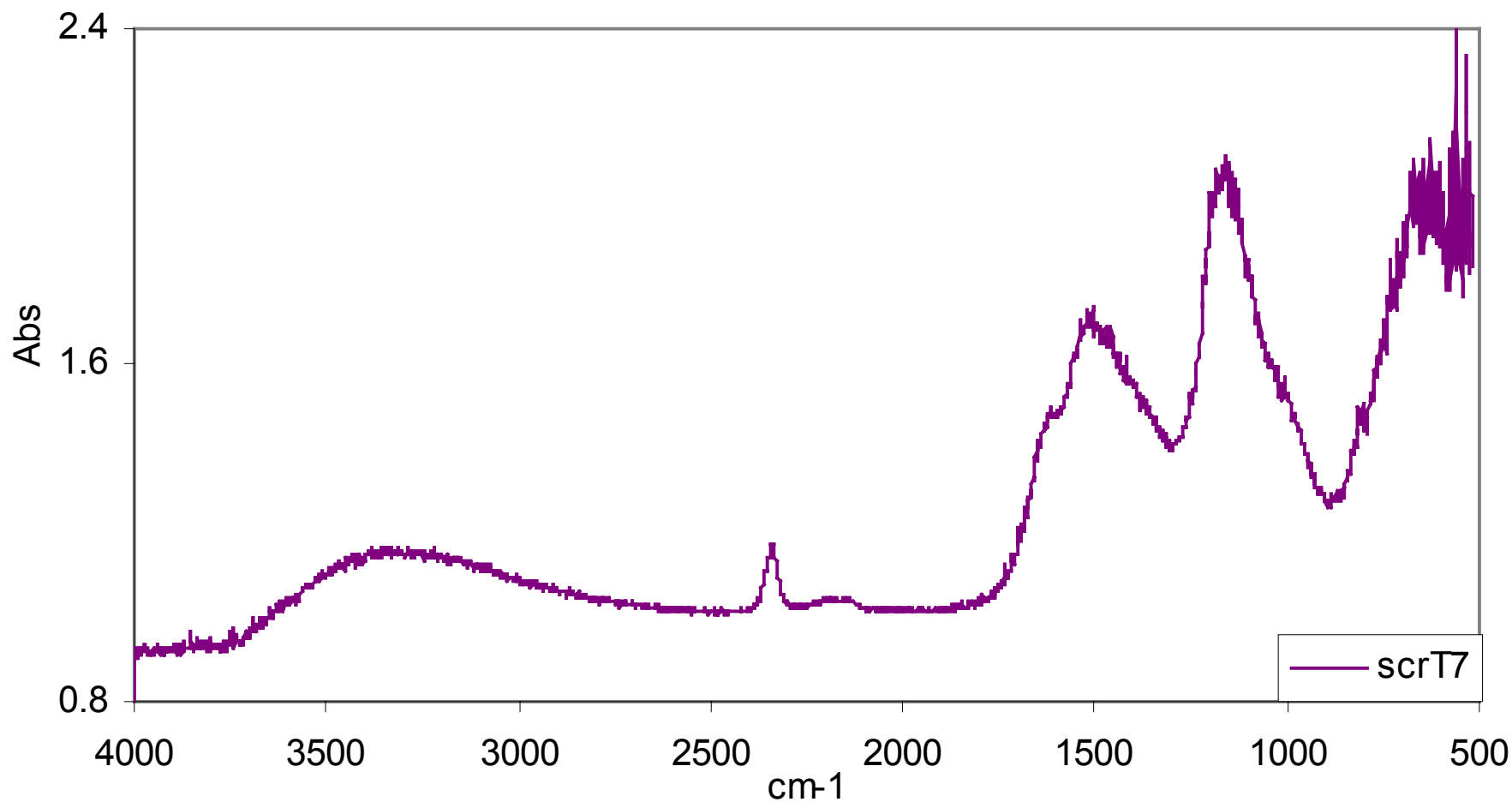
DRIFTS Spectra of Samples in Group B (250 ~ 300°C)

Spectra of samples in Group B match to cyanuric acid with a characteristic 1850 cm^{-1} band representing cyclic imido configuration



DRIFTS Spectrum of Sample in Group D (450°C)

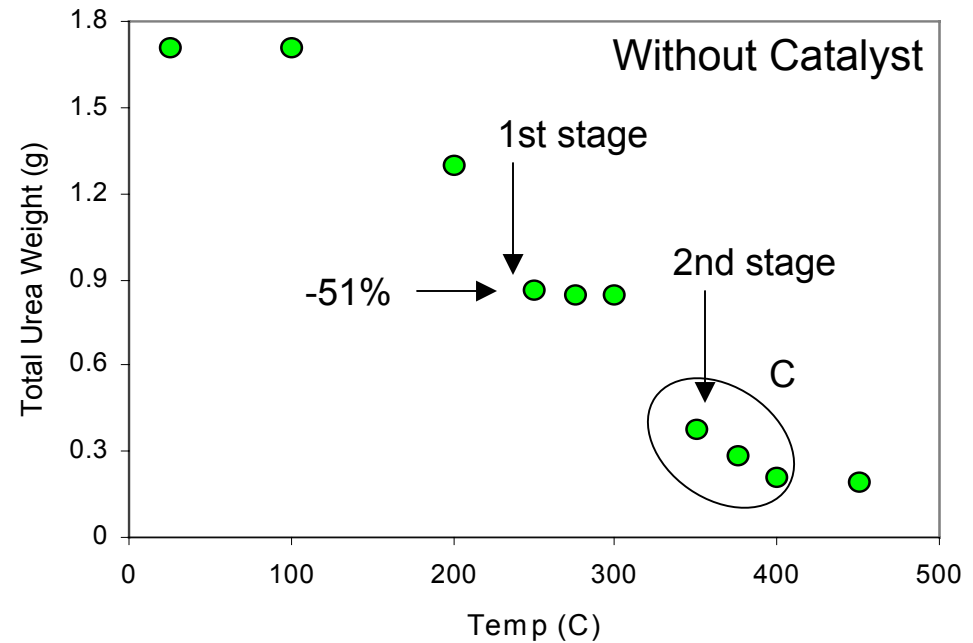
- Melamine bands of the final brown product are observed at 2345, 1514 and 1165 cm^{-1}
- Iso-cyanate band ($-\text{N}=\text{C}=\text{O}$) can also be seen at 2200 cm^{-1}



Comparison of Urea Decomposition with And without Catalyst

(A) without catalyst (Siemens V-W-Ti):

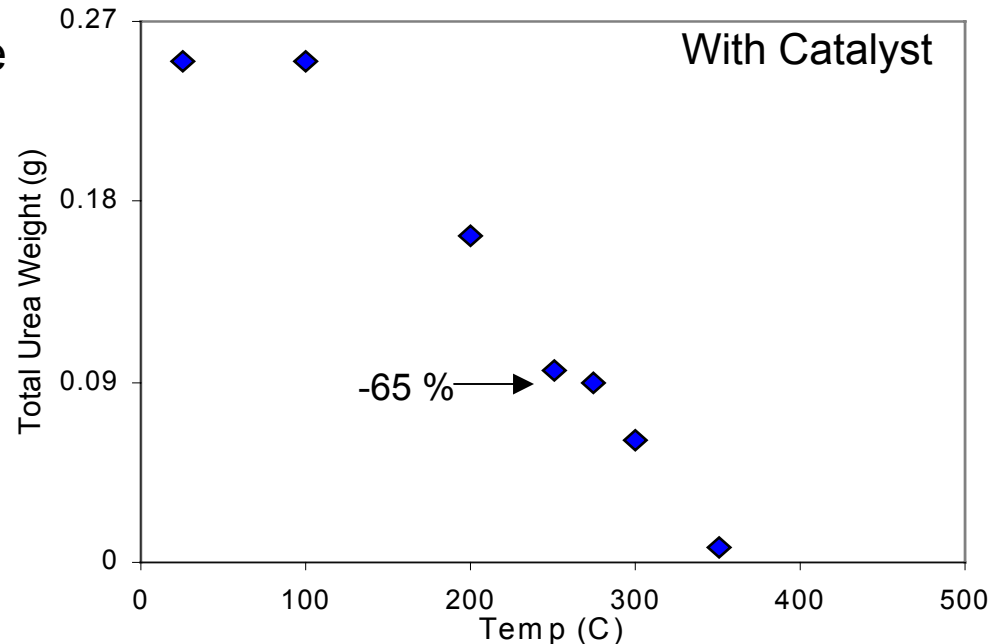
The decomposition of urea follows a normal two-step process; first to cyanuric acid and second to the final polymeric products



(B) with catalyst (Siemens V-W-Ti):

The decomposition of the 2nd stage is accelerated

- Final products similar to samples in Group C
- High temperature component (final products in (A)) eliminated



Products of final decomposition stage are resistant to SCR catalytic reactions

(A) Siemens catalyst is mixed with group B samples (Cyanuric acids) in 2:1 ratio:

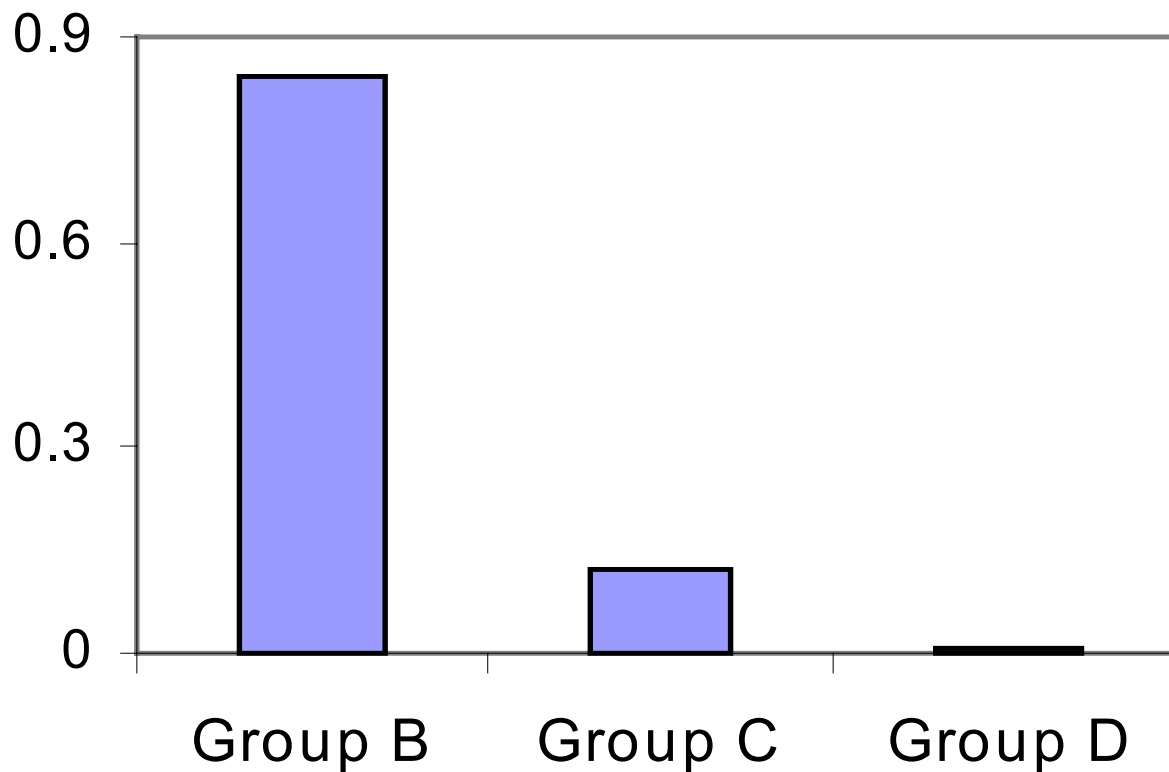
84 % loss at 320°C

(B) Siemens catalyst is mixed with the brown pipe deposit (Group C samples) in 2:1 ratio:

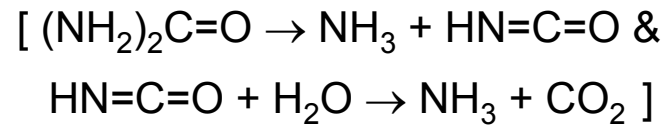
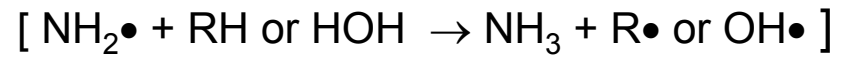
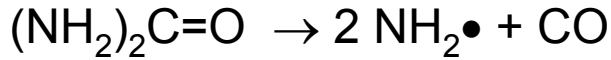
only 12 % loss at 320°C

(C) Siemens catalyst is mixed with the group D samples (melamines) in 2:1 ratio:

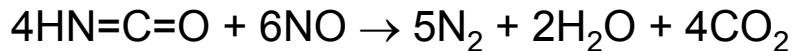
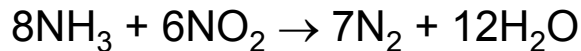
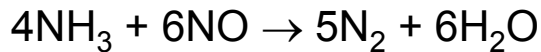
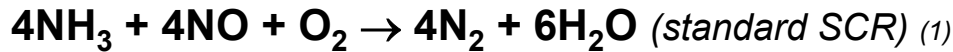
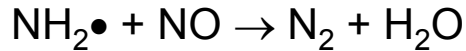
almost no loss observed at 320°C



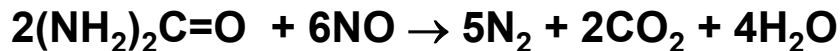
Urea-SCR Mechanism



Desirable Reduction

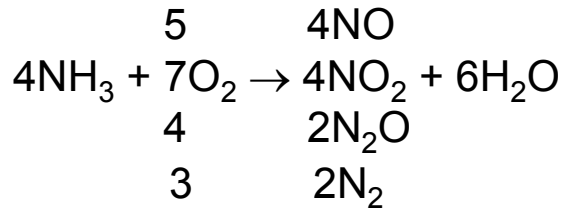
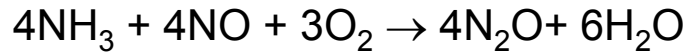
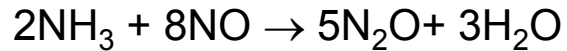


Direct Urea Reduction

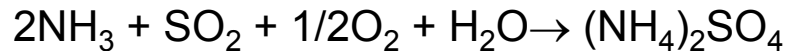
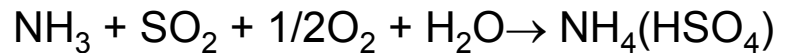


This one seems to match the stoichiometric ratio

Undesirable Reaction/Oxidation



Undesirable Degradation

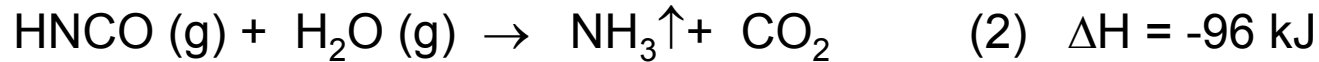
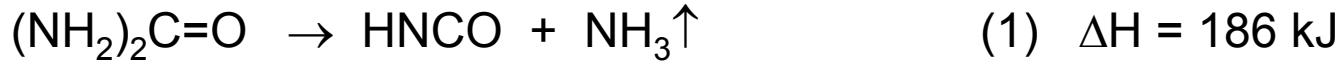


At $T < 200^\circ\text{C}$, solid formation



Why is there a stoichiometric imbalance in urea hydrolysis?

- **Theoretical limit:**

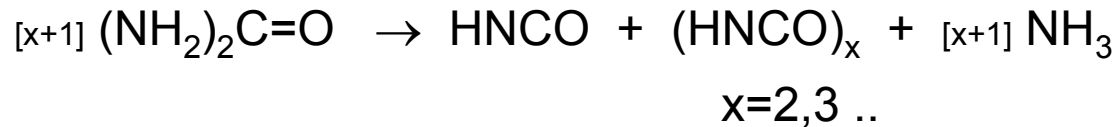


Under theoretical limit, one mole of urea generates two moles of NH_3 , and can reduce 2.5 moles of NO , at most. (This implies that 0.9 g of urea is required to reduce 1 g of NO)

- **Experimental Results**

-Process (2) is not kinetically favored and requires catalyst

-Process (1) involves non-hydrolyzable products



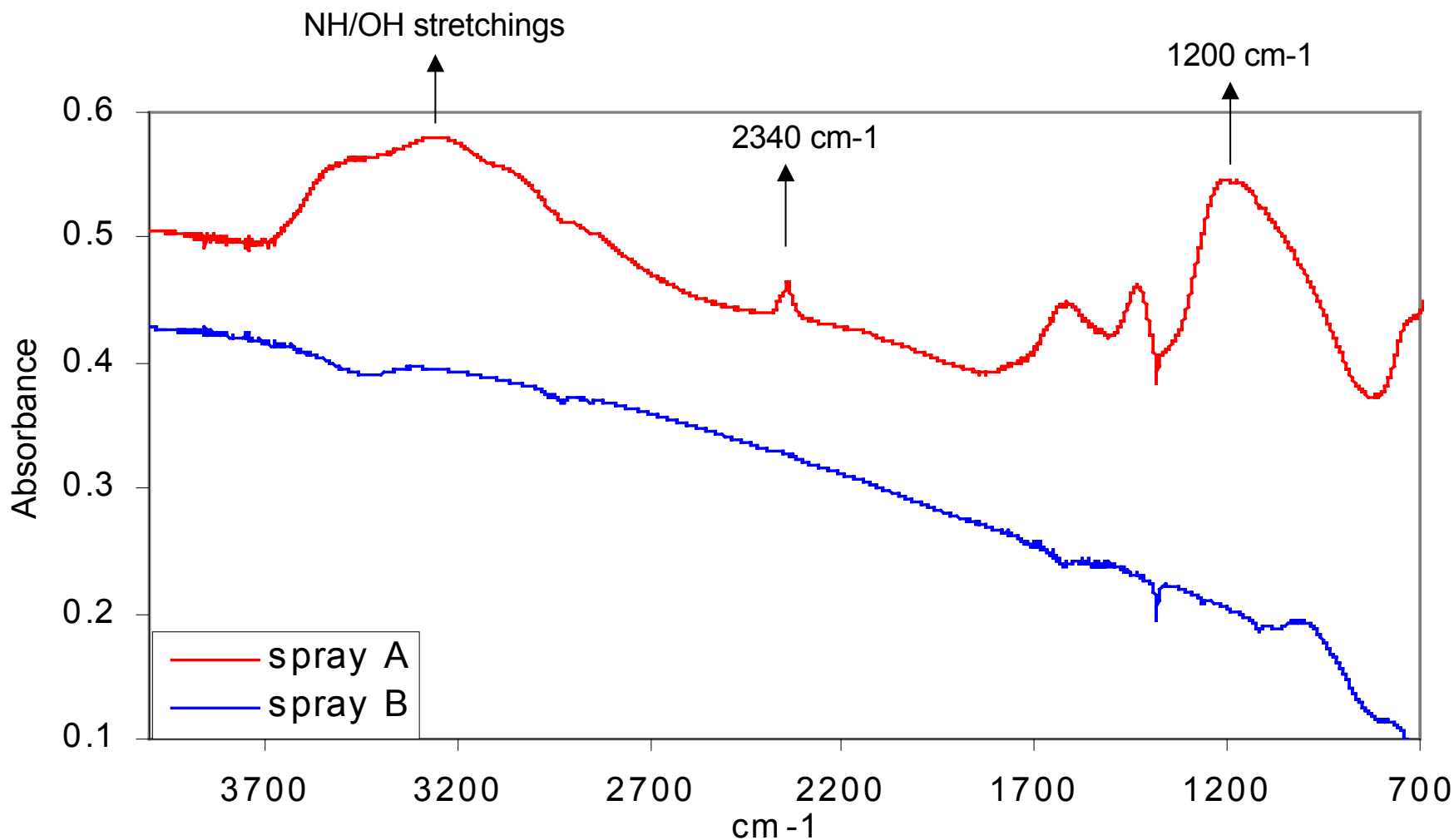
which may form deposits on the pipe wall

-Monitoring CO_2 yield should reflect the reaction percentage of HNCO generation

-Appropriate catalysts and additives in urea solution can speed up the 2nd stage decomposition

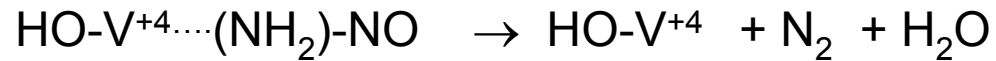
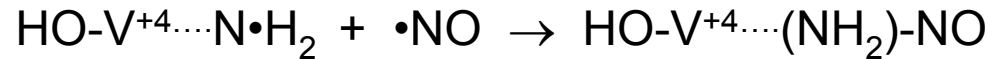
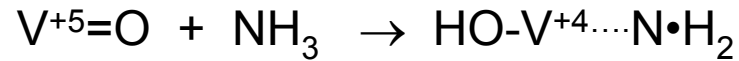
A good urea spray minimizes the deposit formation

- The DRIFTS spectrum of the wall deposit sample using spray A shows rich hydrocarbon signatures which can be attributed to melamine complexes, $(\text{HNCO})_x$
- The baseline increase towards high frequency is caused by soot scattering

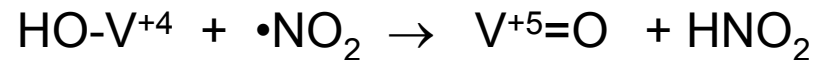


Urea-SCR Mechanism for Vanadium-based Catalysts

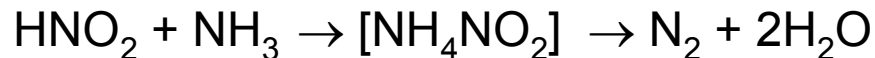
Activation of NH₃ leads to a reduction of vanadia surface



NO₂ radicals re-oxidize the surface

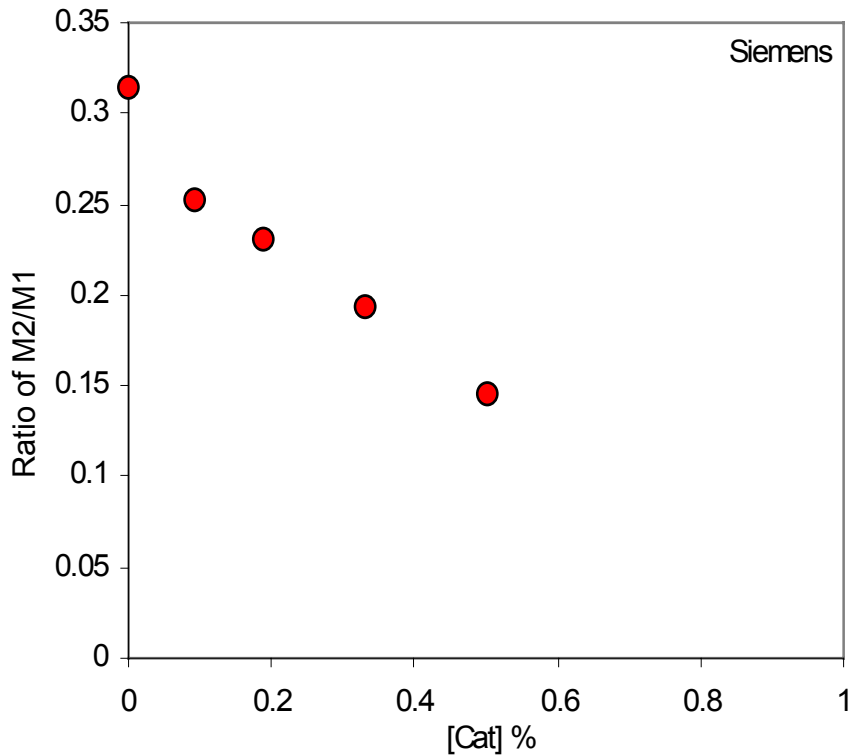


HNO₂ begins to neutralize adsorbed NH₃



- **Surface redox of V=O sites determines the efficacy of SCR catalyst**
 - **DRIFTS data are consistent with this mechanism**

Concept of Additive Technology for Urea-SCR



- The decomposed products after the 2nd stage of urea decomposition should be avoided due to their resistance to catalytic reactivity
- Elimination of the 2nd stage becomes an indicator in determining catalytic efficacy

Comparison of $\Delta M_2/\Delta M_1$ for modified catalysts

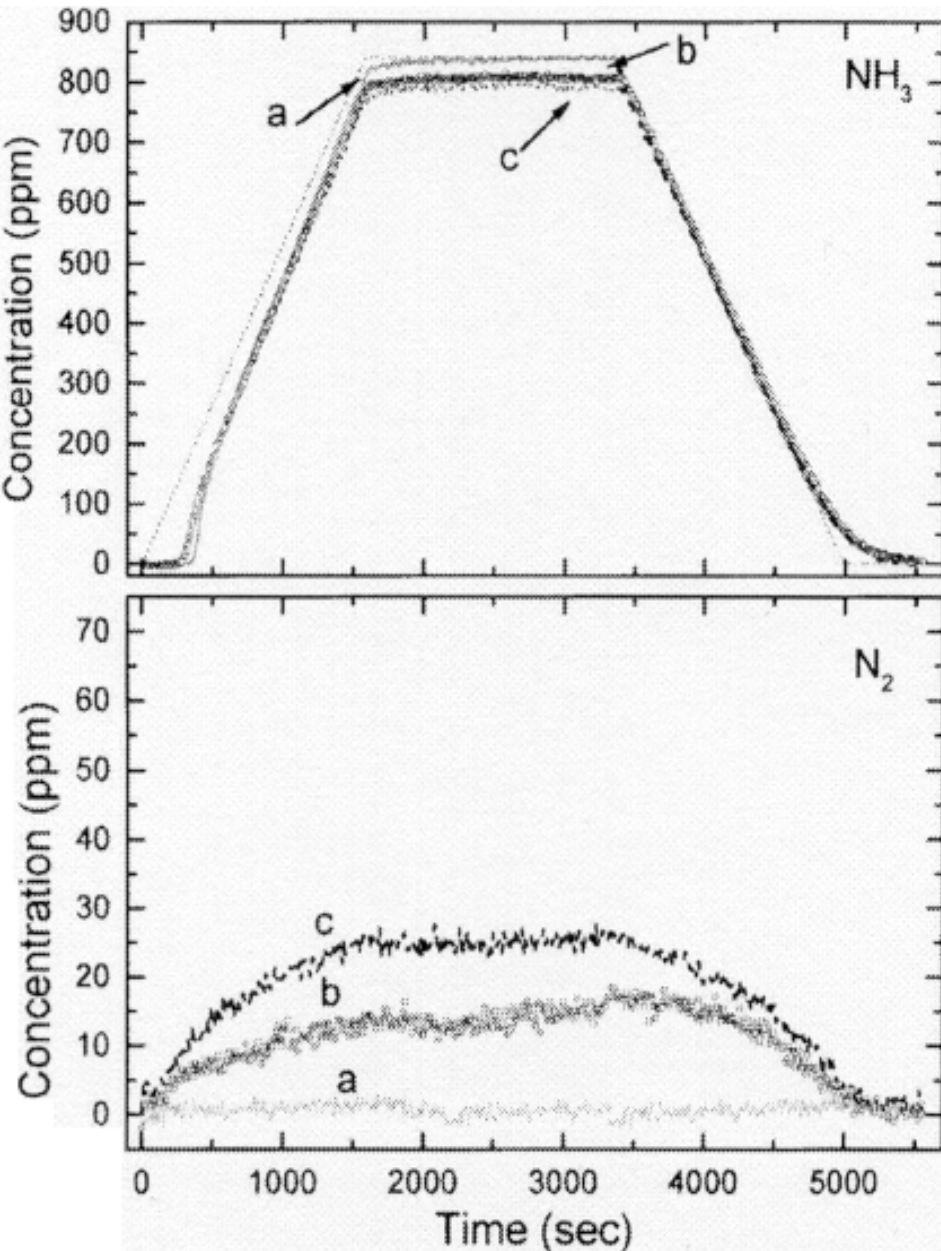
Sample	ΔM_1	ΔM_2	$\Delta M_2/\Delta M_1$
Urea/Cat in 3:1	9.0	1.75	0.194
Urea/CatA in 3:1	9.7	1.30	0.134
Urea/CatB in 3:1	7.6	1.47	0.193

CatA: an oxidizer

CatB: a reducer

- Oxidizers can be either doped in the urea solution or mixed in the V-W-Ti catalysts

NH₃ oxidation can be partly accounted for stoichiometric imbalance of urea



- NH₃ adsorbs on the catalyst surface
- Above 360°C, N₂ is formed (oxidation of NH₃)
- None of the nitrogen oxides are formed

a: 340°C

b: 380°C

c: 400°C

Nova et al., *Cat. Today* 60, 73 (2000)

CONCLUSIONS

Thermal decomposition of urea involves two stages

- The 1st stage (NH₃ generation stage) involves formation of biuret/cyanuric acid and the 2nd stage (NH₃ consumption stage) involves formation of polymeric melamine complexes
- The decomposition of the 2nd stage can be accelerated by V₂O₅/TiO₂/WO₃ catalyst
- Polymeric products are resistant to catalytic reaction and are responsible for non-stoichiometric urea consumption
- The ratio of $\Delta M_2/\Delta M_1$ can be developed as an indicator to differentiate urea-SCR catalysts

Effective urea decomposition requires a close contact with catalyst

- The injector distance and spray prior to catalyst surface should be kept appropriate

Redox reaction of V⁺⁵=O site is the critical step in urea-SCR mechanism

- NO₂ (or other oxidizers, SO₂) assists SCR reduction
- Additive technology of using oxidizers in urea solution to rejuvenate catalyst surface