# Selectivity and Lifetime Effects in Zeolite-Catalysed Baeyer–Villiger Oxidation Investigated in Batch and **Continuous Flow**

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In this manuscript, we investigate the kinetic, mechanistic and lifetime aspects of the Baeyer-Villiger oxidation of cyclohexanone with Sn- $\beta$  as catalyst and H<sub>2</sub>O<sub>2</sub> as oxidant, with the aim of: 1) elucidating the overall reaction network, 2) closing the carbon balance, particularly at high levels of conversion, and 3) examining the intensification of this process in the continuous regime. The results presented herein conclusively demonstrate that this reaction is highly selective for the desired product (*ɛ*-caprolactone) only below conversions of 60%. Above this level of conversion, unavoidable hydrolysis of  $\varepsilon$ -caprolactone to 6-hydroxyhexanoic acid is observed, which consumes the desired product and leads to a reduction in catalytic activity through poisoning. By elucidating the reaction network and working under optimised conditions, we show the potential viability of this methodology to operate continuously over a 180 h period, both at high levels of productivity (324 g (cyclohexanone converted)  $cm^{-3}$  (reactor volume) kg<sup>-1</sup> (catalyst) h<sup>-1</sup>) and selectivity (70% at 60% conversion). Over 5000 substrate turnovers were observed during this period, an order of magnitude higher than previously noted for this particular catalyst system.

#### Introduction

The Baeyer-Villiger oxidation (BVO) reaction has been widely studied over the past 100 years, since its discovery in 1899.<sup>[1]</sup> It has demonstrated itself to be an especially profitable method to convert ketones, readily available building blocks in organic chemistry, into more complex and valuable esters and lactones.<sup>[2]</sup> A key example of this chemistry is the industrially employed BVO of cyclohexanone (CyO) to yield  $\varepsilon$ -caprolactone, a key monomer in the bulk chemical industry.<sup>[3]</sup> Traditionally, this chemistry has been performed using peracid-based oxidants, such as mCPBA (meta-chloroperbenzoic acid). Unfortunately, such oxidants possess several drawbacks, including the co-production of byproducts (carboxylic acids), low active oxygen content, potential explosiveness and a requirement for undesirable chlorinated solvents.<sup>[4]</sup> Additionally, they typically demonstrate poor levels of selectivity when other functional

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groups, such as C=C double bonds, are present in the substrate.

To overcome these problems, much effort has been made towards replacing such oxidants with greener, less polluting and potentially less expensive oxidants.<sup>[5]</sup> A key example is hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>).<sup>[6]</sup> In this case, a suitable catalyst is required to allow H<sub>2</sub>O<sub>2</sub> to interact with the ketone substrate. Activation of the oxidant, in addition to the substrate, may therefore be required. Amongst several potential catalytic materials, the Lewis acidic zeolite, Sn- $\beta$ , has conclusively been shown by Corma et al.<sup>[3a]</sup> to be the most active, selective and suitable catalyst for BVO. This material appears to be uniquely able to polarise the carbonyl group of the substrate, thus making it more prone to nucleophilic attack by the oxidant, H<sub>2</sub>O<sub>2</sub>, without activating the oxidant molecule, thus resulting in high levels of chemoselectivity even when multiple functional groups are present. The most widely accepted mechanism for this reaction is described in Scheme 1.

Although much work has subsequently been devoted towards scalable synthesis of Sn- $\beta$ ,<sup>[7]</sup> and the development of novel catalytic processes catalysed by the same (or similar) material(s), research focusing on the Sn- $\beta$ -catalysed BVO reaction itself is lacking, despite the considerable industrial potential. Consequently, several questions and challenges remain. Greatest amongst these are: i) the need to identify and optimise all the kinetic parameters of the reaction, ii) the requirement to identify the byproducts, and hence close the low carbon balance often observed, and iii) investigation of the potential scalability of the system, particularly in the continuous regime. These three challenges constitute the focus of this work.



Scheme 1. Molecular mechanism proposed for the BVO of cyclohexanone catalysed by Sn- $\beta$ .

## **Results and Discussion**

#### Impact of kinetic parameters

According to our optimised synthesis protocol,<sup>[7a]</sup> a range of Sn- $\beta$  catalysts were prepared from a commercially available Al- $\beta$  precursor material (SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>=38, from Zeolyst). Sn loadings of 1, 2, 5 and 10 wt% were achieved by incorporating Sn into the vacant framework sites by solid-state incorporation (SSI) with Sn<sup>II</sup> acetate as the tin source.

The synthetic and spectroscopic information of these materials was recently extensively described in a detailed manuscript,<sup>[7a]</sup> and for brevity will not be shown here. In general, isomorphously substituted Sn<sup>IV</sup> sites were almost exclusively observed up to a loading of 5 wt%, although beyond this loading, in-active, extra-framework Sn<sub>x</sub>O<sub>y</sub> sites were also observed. Accordingly, our primary catalyst, henceforth denoted 2 Sn- $\beta$  (38)<sub>550</sub>, consisted of 2 wt% Sn incorporated into the vacant framework sites of zeolite  $\beta$  (initial SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> = 38) by SSI at 550 °C, as this loading highly

ing is consistent with a material possessing highly active, isolated  $\mathsf{Sn}^{\mathsf{IV}}$  sites.

We first explored the activity of this material for the BVO of CyO under conditions similar to those reported originally by Corma et al. (Figure 1).<sup>[3a]</sup> However, reaction temperatures of 100 °C (internal temperature) were employed, instead of 90 °C. Under the chosen reaction conditions,  $2 \operatorname{Sn}-\beta$  (38)<sub>550</sub> is a highly active catalyst, converting >60% of the CyO reactant in 1 h, and >90% in <6 h. Initially, the system is highly selective (90%) for caprolactone, demonstrating this to be the primary reaction product. However, a remarkable decrease in caprolactone selectivity and total carbon balance is observed as the conversion increases beyond 60%. Indeed, caprolactone selectivity and total carbon balance from >90% during



**Figure 1.** Catalytic activity of  $2 \operatorname{Sn}-\beta$  (38)<sub>550</sub> for the BVO of cyclohexanone. Left: Selectivity to caprolactone and total carbon balance, both as a function of cyclohexanone conversion. Right: Conversion and caprolactone yield versus time.

the first 30 minutes of reaction, to 50% after 6 h of reaction. It is also evident that the catalytic rate rapidly decreases above conversion levels of 60%. According to this kinetic profile, caprolactone yield very quickly reaches 40%, but then stagnates and eventually decreases slightly at the highest levels of conversion. This observation, coupled with the corresponding decrease in carbon balance at elevated conversion, strongly points towards the formation of consecutive byproducts throughout the reaction period. No additional products could be detected by GC, which is the most routinely applied analytical technique in this area of research. The identity of these byproducts is discussed later in the manuscript.

We subsequently investigated the impact of the Sn loading of the catalyst (Figure 2). In these experiments, various samples



Figure 2. Catalytic activity of various Sn- $\beta$  samples containing 2–10 wt% Sn for the BVO of cyclohexanone. Left: Conversion versus time. Right: Selectivity to caprolactone as a function of cyclohexanone conversion.

of Sn- $\beta$ , containing either 2, 5 and 10 wt% of tin, were tested at a fixed amount of Sn relative to cyclohexanone, that is, the catalyst mass was adjusted so that the same amount of Sn was employed in the reactor (1 mol% relative to CyO). We note here that the theoretical amount of Sn that can be incorporated into dealuminated zeolite (SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>=38) is approximately 9 wt%, that is, Sn loadings up to and beyond the theoretical maximum loading were tested. Utilisation of high Sn loadings can be beneficial to obtain high space-time yield values and enhance process profitability. Furthermore, catalysts containing different Sn contents may exhibit different selectivity trends.

As can be seen, reactions performed by using the same substrate/metal molar ratio with  $2Sn-\beta$  and  $5 \text{Sn-}\beta$  presented almost identical catalytic activities in terms of conversion (and hence turnover frequency (TOF)). However, a decrease in activity and TOF was observed as the Sn loading of the catalyst was increased to 10 wt%. The decrease in the activity of this sample (initial (5 min) TOF decreasing from

370  $h^{-1}$  (2 Sn- $\beta$ ) to 199  $h^{-1}$  (10 Sn- $\beta$ )) indicates that spectator Sn species are present at higher loadings, in agreement with our recent studies of transfer hydrogenation and glucose isomerisation over the same materials.<sup>[7]</sup> Accordingly, all kinetic parameters were optimised in the presence of  $2Sn-\beta$  so as to avoid the potential influence of spectator Sn sites.

At all levels of conversion, each catalyst exhibits comparable selectivity, indicating that the formation of spectator Sn sites does not adversely affect the reaction network, nor catalyse the formation of byproducts or consecutive reaction products. Furthermore, the residual Brønsted acid sites from unreacted silanol nests do not participate in the reaction, indicating that conversion alone determines overall caprolactone selectivity. Accordingly, opportunities to improve selectivity by modifying catalyst composition appear unavailable.

As the reaction temperature is decreased from 100 to 40°C, a clear decrease in CyO conversion is observed. Kinetic analysis of the time online data reveals that the catalytic reaction fits better as a second-order reaction under the standard conditions (Figure S1 in the Supporting Information), and an activation energy of 51.1 kJ mol<sup>-1</sup> was determined. This barrier is comparable to the value reported by Boronat et al.<sup>[8]</sup> for analogous materials under comparable reaction conditions (45 kJ mol<sup>-1</sup>).

As observed in Figure 3 (left), regardless of the reaction temperature, high (>70%) selectivity to caprolactone was only observed when CyO conversion levels were kept < 50-60%, after which point selectivity to caprolactone, and total carbon balance, drops noticeably. The selectivity trend is clearly comparable at all reaction temperatures, within experimental error, and selectivity seemingly only depends on the extent of conversion. This indicates that the



Figure 3. Catalytic activity of 2 Sn- $\beta$  (38)<sub>550</sub> for the BVO of cyclohexanone at various temperatures. Left: Conversion versus caprolactone selectivity during BVO of cyclohexanone between 40 and 100 °C. Right: Arrhenius plot for 2 Sn- $\beta$  (38)<sub>550</sub> for the BVO of cyclohexanone (y = 10.11431-6146.840 x).

side reactions or consecutive reactions have comparable activation energies to the BVO reaction, and that high(er) levels of selectivity cannot be obtained through kinetic control.

To determine the effect of  $H_2O_2$  concentration on catalytic rate, a series of experiments with different H<sub>2</sub>O<sub>2</sub>/ketone ratios were performed, with all other parameters, for example, Sn content (1 mol%), reaction temperature (100 °C) and catalyst choice  $(2 \text{ Sn}-\beta (38)_{550})$  remaining unchanged. However, as H<sub>2</sub>O<sub>2</sub> is used as an aqueous solution, the concentration of H<sub>2</sub>O also changes during these experiments. The initial concentration of hydrogen peroxide was varied from 0.035 to 1 m, representing a range of H<sub>2</sub>O<sub>2</sub>/ketone of ratios 0.1 to 3.0 (under typical conditions, a ratio of 1.5 was employed). The apparent rate constant





Figure 4. Left: Effect of  $[H_2O_2]$  on the rate of the BVO of CyO at 100 °C. Right: Impact of relative Sn content on the rate of BVO at 100 °C.

 $(k_{appr}$  units  $M^{-1} s^{-1}$ ) at each  $H_2O_2$ /ketone ratio was determined at the very initial stages of the reaction, that is, in the linear region of the kinetic plot, and are represented in Figure 4. Between  $H_2O_2$ /ketone ratios of 0.1 and 0.75, a first-order dependence on  $H_2O_2$  is observed, with  $k_{app}$  increasing linearly with  $[H_2O_2]$ . However, above this  $H_2O_2$ /ketone ratio,  $k_{app}$  reaches a plateau, within experimental error, and the reaction becomes zero order with respect to the oxidant. Once in the zero-order regime, excess  $H_2O_2$  does not interfere with the intrinsic kinetics of the system. However, at the highest oxidant concentration, caprolactone selectivity at all levels of ketone conversion drops somewhat (Figure S2 in the Supporting Information). This indicates that  $H_2O_2$  and/or  $H_2O$  (as  $H_2O_2$  is used as an aqueous solution) may be involved in a consecutive reaction that decreases the total carbon balance.

Under the conditions reported by Corma et al., [3a] Sn contents of 1 mol% (relative to CyO) are typically employed. Accordingly, the mass of  $2\,\text{Sn-}\beta\,(38)_{\rm 550}$  was varied so that Sn contents of 0.1-3 mol%, relative to CyO, were utilised to determine the impact of Sn content. The  $k_{app}$  ( $M^{-1}s^{-1}$ ) value at all Sn contents was calculated at low conversions to minimise the impact of product-induced deactivation. Between 0.1-1 mol% Sn, a linear relationship between  $k_{app}$  and Sn content is observed. However, at very high Sn loadings,  $k_{app}$  is lower than anticipated, indicating that some mass transfer limitations are present when large masses of catalyst are used. Accordingly, all further experiments were conducted at Sn contents of 1 mol% or lower, consistent with the reaction being in the kinetic regime (also evident from the linear Arrhenius plot). In terms of caprolactone selectivity, the trend obtained was maintained throughout all experiments, that is, varying the Sn content within the reactor did not overtly impact caprolactone selectivity at any level of conversion.

# Identification of byproducts and closing the carbon balance

To fully identify the reaction network, we subsequently turned our attention to identifying the nature of the unknown byproducts that must be present, accounting for the missing carbon balance. From previous studies, the most likely byproducts include 6-hydroxyhexanoic acid (6-HHA), formed through caprolactone hydrolysis, and adipic acid (AA), formed by the oxidation of 6-HHA.<sup>[9]</sup> Although we were able to record the FTIR spectra of four potential reactant species (CyO, caprolactone, 6-HHA and AA, Figure S3 in the Supporting Information), the relative overlap of each C=O signal means that identification of each potential compound in a mixture of all compounds was not feasible (Figure S4 in the Supporting Information).

Although the presence of the solvent inhibits identification of all potential species within the reaction solution by <sup>1</sup>H NMR spectroscopy under normal con-

ditions, the relatively high boiling points of CyO and all the potential products allowed us to almost completely evaporate the solvent (1,4-dioxane, boiling point 100 °C) prior to analysis, and consequently obtain satisfactory qualitative data. This immediately revealed the presence of distinct resonances of CyO, caprolactone and 6-HHA in various reaction samples. Unfortunately, all <sup>1</sup>H NMR resonances of adipic acid overlap with CyO and 6-HHA (Figures S5 to S8 in the Supporting Information), and hence AA cannot be conclusively identified by <sup>1</sup>H NMR spectroscopy.

Quantification of the (by)products by <sup>1</sup>H NMR spectroscopy was achieved by calibrating a capillary containing a known amount of tetramethylsilane (s,  $\delta = 0.0 \text{ ppm}$ ) against known standards (Figure S9 in the Supporting Information), and placing this capillary within the NMR tubes of various time online samples. To verify this approach, the concentrations of caprolactone as determined by GC-FID (biphenyl internal standard) and <sup>1</sup>H NMR spectroscopy were compared. All values were found to be identical within 1-6% error, verifying this approach (Table S1 in the Supporting Information). We note here that overlapping signals prevent quantification of CyO by this method, and its concentration was solely monitored by GC-FID. Utilising both GC-FID and <sup>1</sup>H NMR spectroscopy, the initial BVO of CyO was repeated under standard conditions. With the added quantification of 6-HHA, the carbon balance improves from 54% to 88% at the highest levels of conversion (Figure 5). This clearly demonstrates that as the conversion increases, selectivity towards 6-HHA increases dramatically, strongly indicating that the overall reaction contains two particular steps: 1) BVO, yielding caprolactone, and 2) hydrolysis of caprolactone to 6-HHA.

To determine the concentration of AA, which may be present as a deep oxidation product, <sup>13</sup>C NMR spectroscopy and HPLC were utilised; authentic standards revealed that AA could be separated and quantified by HPLC, and that it possesses a distinct <sup>13</sup>C resonance at 175.82 ppm. Although Cavani

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Figure 5. Time online analysis of BVO of CyO at 100 °C monitored by GC and  $^{1}$ H NMR, catalysed by 2 Sn- $\beta$  (38)<sub>550</sub>.

et al.<sup>[10]</sup> observed AA as a deep oxidation product during the BVO of CyO with titanium silicalite-1 as catalyst, only trace amounts (<3 mol%) of this byproduct were observed during the entire reaction period (Figure S10 in the Supporting Information). We attribute the minor amount of this deep oxidation product in this particular to 1) the change in catalyst utilised (titanium silicalite-1 is a catalyst known to produce 'OH radicals, which may readily oxidise 6-HHA), and 2) the presence of 1,4-dioxane as solvent, which acts as an 'OH radical scavenger.<sup>[10]</sup>

To further close the carbon balance (91% including AA), the spent catalytic materials extracted from the reactor after reaction were also analysed by thermogravimetric analysis (TGA; Figure S11 in the Supporting Information, including detailed experimental description). The mass losses observed upon heating the ex reactor catalyst were compared with those mass losses observed from known standards of CyO, caprolactone, 6-HHA and AA, pre-adsorbed onto a reference  $2 \text{Sn-}\beta (38)_{550}$ powder. Thus, TGA of the used catalyst allowed us to determine the type (from the desorption temperature) and quantity (by the mass loss observed at said temperature) of adsorbed carbon present. In addition to some residual solvent, a considerable amount (>11 wt%) of caprolactone, and a small amount (3 wt%) of 6-HHA were detected. In total, this corresponded to approximately 5% of the original carbon species introduced into the reaction at the start of the process, and thus raises the carbon balance under the typical BVO conditions to 96%.

Over the first hour of the reaction, no oligomeric products of caprolactone and/or 6-HHA, were detected by NMR spectroscopy or gel permeation chromatography (GPC). However, at more extended reaction times (2-6 h), and higher levels of conversion, some polymeric products could be observed (Figure 6). GPC analysis of these reaction samples revealed these polymeric species to be oligomers of caprolactone, possessing between two and three caprolactone units (Figure S12 in the Supporting Information). This clearly suggests that performing the reaction continuously at high conversion should be avoided so as to minimise the opportunity of fouling by oli-

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Figure 6. Time online analysis of BVO of CyO at 100 °C by <sup>1</sup>H NMR spectroscopy.

gomer formation. The degree of caprolactone oligomerisation likely fully closes the carbon balance at high levels of conversion, although precise quantification of the oligomeric products is not possible at this stage.

#### Caprolactone conversion studies

In an attempt to improve the overall caprolactone selectivity levels-particularly at high levels of conversion-the caprolactone hydrolysis reaction, responsible for the co-production of 6-HHA, was also studied. Although dehydration of 6-HHA to caprolactone could be performed in a second step, obtaining high caprolactone selectivity would lead to improved efficiency and minimise downstream processing.

We first investigated the role of the catalyst in the hydrolysis reaction. To do this, a solution of caprolactone in 1,4-dioxane (0.2 M) was placed in a round-bottomed flask under the standard reaction conditions, and two separate experiments were performed. In the first reaction (Table 1, entry 1), the typical amount of  $H_2O$  (added by necessity when using 50 wt%  $H_2O_2$ )

Table 1. Extent of caprolactone hydrolysis observed under various reaction conditions.					
Entry	Catalyst	H <sub>2</sub> O [mL]	Conversion [%]		
1	-	0.15	0		
2	2% Sn-β 38	0.15	25		
3	deAl β 38	0.15	1.8		
4	5% Sn-β 38	0.15	23		
5	10% Sn-β 38	0.15	13		
6	2%Sn-β 38	0.3	36		
7	deAl β 38	0	1.1		
8	2% Sn-β 38	0	8		
9	5% Sn-β 38	0	7		
10	10 % Sn-β 38	0	4		
11	2%Sn- $\beta$ 38 recalcined	0	4		
12	2% Sn-β 38	0.3 (50 wt % H <sub>2</sub> O <sub>2</sub> )	62		

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was added to the vessel. In the second experiment (entry 2),  $2 \text{Sn-}\beta$  was also added to the reactor, in addition to H<sub>2</sub>O. This control experiment was to verify whether hydrolysis of caprolactone proceeded in an uncatalysed manner, or whether the heterogeneous material promoted the reaction. In both cases, consumption of caprolactone and the formation of 6-HHA was monitored by GC and <sup>1</sup>H NMR spectroscopy (Table S2 in the Supporting Information). In the absence of catalyst (Table 1, entry 1), *no* conversion of caprolactone was observed. In contrast, in the presence of the catalyst, 25% conversion of caprolactone to 6-HHA (at >95% selectivity) was observed. This strongly indicates that some catalyst functionality (potential Lewis acidity, Brønsted acidity, or defect sites) is required to catalyse the hydrolysis reaction.

To deduce the nature of the catalyst functionality responsible for the hydrolysis reaction, the activity of various samples of Sn- $\beta$  for the hydrolysis reaction alone was explored. In the absence of Sn (entry 3), dealuminated zeolite  $\beta$  demonstrates extremely low reactivity for the hydrolysis reaction, indicating that defect sites and residual Brønsted acid sites of the zeolite framework alone are not responsible for caprolactone hydrolysis. In contrast, Sn- $\beta$  (possessing between 2 and 10 wt% Sn, entries 2, 4 and 5) demonstrates substantial activity for hydrolysis, with up to 25% conversion being observed over a fourhour reaction period. Interestingly, the relative activities of the 2, 5 and 10 Sn- $\beta$  samples for caprolactone hydrolysis is identical to the relative activities observed with these samples for the BVO reaction itself (Figure 2). Unfortunately, this strongly indicates that the same Sn sites required for BVO are responsible for caprolactone hydrolysis. Thus, catalyst modification methodologies are unlikely to be able to remove the hydrolysis side reaction, and 6-HHA formation is likely unavoidable under these reaction conditions. Quantification by using the tetramethylsilane capillary confirmed 6-HHA as the main product with a selectivity > 90% in all of these cases, although trace amounts of oligomers could also be observed at extended reaction periods (Figure S13 in the Supporting Information). Surprisingly, even in the absence of additional water, conversion of up to 8% caprolactone to 6-HHA was still observed when using different Sn- $\beta$  catalysts (entries 7 to 10). We subsequently repeated this series of experiments utilising freshly calcined Sn- $\beta$  as opposed to Sn- $\beta$  that had been stored at ambient conditions for approximately 4-7 days (entry 11). Although caprolactone conversion was reduced, it was not eliminated completely, showing that even trace amounts of water lead to hvdrolvsis.

Additionally, we studied the effect of  $H_2O_2$  addition (entry 12). Whilst higher caprolactone conversion was observed when  $H_2O_2$  is present alongside  $H_2O$  (62% (entry 12) versus 36% (entry 6)), AA was still not observed by <sup>13</sup>C NMR spectroscopy (Figure S14 in the Supporting Information), and selectivity to 6-HHA was still >90%. The high selectivity to 6-HHA observed even in this case strongly indicates that ring opening, and not deep oxidation, remains the dominant consecutive reaction. We hypothesise that the increased rate of ring opening in the presence of  $H_2O_2$  may be due to the lower pH/pKa of the solution and/or the presence of cationic stabilisers in the  $H_2O_2$  solution, both of which may increase the rate of ring opening. Finally, we investigated the temperature dependence of the hydrolysis reaction catalysed by Sn- $\beta$ , obtaining an  $E_{act}$  of 37 kJ mol<sup>-1</sup> (Figure S18 in the Supporting Information), comparable to that of the BVO reaction. As the reactions are consecutive, effort should be made to control the extent of conversion, and to use the conversion versus selectivity relationship to maximise the selectivity to caprolactone.

#### Intensification and catalyst stability in continuous flow

Having identified the nature of the byproducts present during BVO, we investigated the potential of each of the (by)products to poison the catalyst (product-induced poisoning), as this may prohibit continuous operation. Indeed, the large decrease in catalytic rate observed after 1 h of batch reaction (Figure 1) indicates product-induced poisoning being present. Accordingly, we repeated the standard BVO reaction at 100 °C (Figure 1) in the presence of various quantities of the reaction (by)products (particularly caprolactone, water and 6-HHA; AA was not studied owing to its low concentration throughout the reaction period). In each case, the conversion of CyO was used to determine the kinetics of the reaction as a function of the amount of (by)product added. We note here that as H<sub>2</sub>O<sub>2</sub> is used as an aqueous solution (50 wt%), a 2.83:1 mole ratio (i.e., 283 mol%) of H<sub>2</sub>O relative to CyO is unavoidably present at the beginning of the reaction. However, assuming a totally selective oxidation process occurs, an additional 150 mol% can form during the reaction. In these studies, therefore, the amount of additional water added to the vessel represents this additional 150 mol%, that is, at 0 mol%  $\rm H_2O$  by product added, the initial 283 mol% water is still present.

As seen in Figure 7, each of the products influences the initial rate of reaction to a particular extent. Caprolactone, the desired product, leads to a decrease in the initial rate, but only by approximately 20% even at relatively high, that is, 50 mol%, concentrations. Water and 6-HHA, on the other hand, strongly influence the initial catalytic activity. The initial



**Figure 7.** Effect of byproduct addition on the initial rate of BVO observed with 2 Sn- $\beta (38)_{550}$ . Inverse rate constants were determined by measuring the decrease in CyO concentration as a function of reaction time by GC-FID.



rate of reaction is found to decrease by approximately 50% when 50 mol% 6-HHA, relative to CyO, is added, and water inhibits the rate by approximately 40% at a byproduct level of 50 mol% (which corresponds to a  $H_2O_2$  conversion level of approximately 33%, assuming total conversion of  $H_2O_2$  to  $H_2O$ during the reaction). This clearly demonstrates that the continuous reactor should be held at a level of conversion consistent with there being as little 6-HHA and H<sub>2</sub>O present as possible. A CyO conversion level of approximately 50-60% (corresponding to a 6-HHA level of approximately 15-25 mol%, and a decrease in rate of 20%) appears to be a good target. The strong decrease in rate observed at 6-HHA levels of 50 mol% corresponds well to the decrease in catalytic rate observed in the initial batch experiments at conversion levels of 60% and above, where 6-HHA begins to become the major reaction product.

Having deduced the impact of the potential reaction products on reaction rate, we subsequently set

about exploring the activity of this system in continuous flow. A continuous plug flow reactor (PFR) offers major advantages over a slurry reactor, including i) improved process control and safety, ii) excellent mass and heat transfer, iii) shorter reaction times, iv) smaller reactor volumes, iv) scalability and v) increased space-time yields. In addition, continuous PFRs allow critical evaluation of a catalyst's stability and lifetime under steady-state conditions. The reactor employed was adapted from a kinetically relevant PFR optimised for the Sn- $\beta$  catalysed isomerisation of glucose to fructose<sup>[11]</sup> and the transfer hydrogenation of carbonyl compounds.<sup>[12]</sup> The kinetic relevance of the reactor for BVO was also fully benchmarked (Figure S19 in the Supporting Information), with testing being performed in the absence of external mass transfer limitations.

According to the product-induced deactivation studies above (Figure 7), we targeted contact times that would lead to a conversion level of approximately 60% so as to minimise the influence of 6-HHA on catalyst lifetime. Initially, a  $H_2O_2$ /ketone ratio of 1.5 was employed, consistent with typical batch experiments. Apart from a very short induction period (Figure 8, left, blue triangles), the catalytic activity remains relatively constant over a period of 180 h, with a steady-state CyO conversion of 60% being observed. No major modifications in selectivity were observed upon moving into the continuous reactor, and the conversion versus caprolactone selectivity trend sits on the same profile as found for the batch reactor at the same  $H_2O_2$ / ketone ratio (Figure 8, right).

Clearly, the Sn- $\beta$ /H<sub>2</sub>O<sub>2</sub> BVO system possesses good levels of stability. Over the course of 180 h, the catalyst performed > 5000 substrate turnovers,<sup>[13]</sup> equivalent to over 50 complete batch reactions. Notably, these TON values are an order of magnitude higher than previously observed for the same catalytic system.<sup>[3a]</sup> Overall, a relative loss of only 15.4% of maximal activity (from 65 to 55%) was observed during this period, even without periodic regeneration being performed. Recalcination of the catalyst bed after 180 h nevertheless restores the





**Figure 8.** Left: Conversion versus time on stream during BVO of CyO in the continuous regime at 100 °C. Right: Selectivity to caprolactone observed at different degrees of CyO conversion in both batch and continuous mode.

initial activity (not shown), demonstrating that the slight decrease in activity is reversible, that is, deactivation is not permanent.

In addition to high levels of stability, performing the reaction in plug flow mode also leads to tremendous improvements in the productivity of the system, even at the same reaction temperatures used for the batch experiments. The space-time yield (STY) at 100 °C in the continuous reactor increases by one order of magnitude relative to the batch reactor system (Table 2).<sup>[14]</sup> Notably, the caprolactone selectivity obtained at the maximum STY of each reactor is also substantially higher in the PFR (70 vs. 39%), although as a function of conversion no substantial improvements are observed at the same  $H_2O_2/$ ketone ratio.

Table 2. Relative performance of Sn- $\beta$ for BVO chemistry in batch and flow.				
Reactor	Space-time	Relative space-	Lactone selectivity @ max.	
type	yield <sup>[a]</sup>	time yield	STY [%]	
batch <sup>[b]</sup>	24.5	1	39	
flow <sup>[c]</sup>	323.9	13.2	70	
[a] Space-time yields were calculated at maximum conversion as grams of reactant converted per cm <sup>3</sup> reactor volume, per hour and per kg of catalyst. [b] Only the liquid volume was used as the reactor volume. [c] Volume of catalyst bed (including diluent) used as the reactor volume.				

We subsequently explored the potential of the system to operate in an oxidant-limited regime. From the batch studies (Figure 4, left), it was shown that similar catalytic rates were observed at a  $H_2O_2$ /ketone ratio of 0.75 as were observed at the typical 1.5 ratio, that is, the BVO reaction is zero order in  $[H_2O_2]$  above this level. Although operating in an oxidant-limited regime would limit the system to <75% CyO conversion, the target level of conversion (50–60%) would still be achieva-



ble, and the decrease in water may limit the caprolactone hydrolysis reaction and product-induced poisoning. We subsequently repeated the continuous experiment at the lower H<sub>2</sub>O<sub>2</sub>/ketone ratio of 0.75, keeping all other experimental parameters, including temperature, flow rate, catalyst mass and reactor volume, identical. A high level of stability is observed in the oxidant-limited regime, although CyO conversion was approximately 10% lower across the entire time period. In terms of activity, the maximum conversion obtained was 51%, dropping to 44% after 180 h, which represents a relative decrease from maximal activity of 13.7%. As such, stability is very slightly improved in the oxidant-limited regime. This may be due to the lower amount of water, or the slightly lower level of conversion in this system, which leads to less 6-HHA formation. Similar improvements in caprolactone selectivity at all overlapping ketone conversion levels were also observed in the oxidant-limited regime, with caprolactone selectivity increasing to 85% at a CyO conversion of 40%. However, given the minimum amount of H<sub>2</sub>O required for ring opening, it is clear that complete suppression of ring opening under these conditions is unlikely.

Operating with less oxidant also leads to major improvements in the  $H_2O_2$ -based selectivity of the reaction (Figure S20 in the Supporting Information). At a  $H_2O_2$ /ketone ratio of 0.75, a  $H_2O_2$ -based selectivity (i.e., moles CyO converted/moles  $H_2O_2$ consumed) of  $85\pm4\%$  was obtained, clearly indicating that most of the peroxide is used selectivity for oxidation. In contrast, a maximum  $H_2O_2$ -based selectivity of only 57% was obtained when a  $H_2O_2$ /ketone ratio of 1.5 was employed under otherwise identical conditions. Clearly, decreasing the concentration of  $H_2O_2$  leads to noticeable improvements in  $H_2O_2$  utilisation, without overly compromising the BVO process itself. Such improvements are of tremendous importance to both process economics and the sustainability of the reaction, particularly given the cost of  $H_2O_2$ .

## Conclusions

The Baeyer–Villiger oxidation of cyclohexanone by  $Sn-\beta/H_2O_2$ was studied in batch and continuous mode, in an attempt to understand the mechanistic aspects of the reaction, and identify its potential scalability. It is demonstrated that the BVO of CyO by Sn- $\beta/H_2O_2$  is a challenging reaction, and that consecutive reactions—particularly the hydrolysis of the primary caprolactone product-can substantially decrease the efficiency (selectivity) and activity (rate) of the process. Largely, this is due to the unavoidable formation of 6-hydroxyhexanoic acid (6-HHA) by caprolactone hydrolysis, which leads to partial poisoning of the Sn- $\beta$  catalyst, and also consumes the desired caprolactone product, decreasing the carbon-based selectivity. Optimising the reaction conditions so as to minimise 6-HHA formation nevertheless shows the potential scalability of this system in the continuous regime. Operating the reaction at conversion levels <60%, at which point 6-HHA formation is less pronounced, results in a stable catalytic system that operates for 180 h without major loss in activity, yielding a turnover number > 5000, and a volumetric productivity of 324 g (ketone

converted) cm<sup>-3</sup> (reactor volume) g<sup>-1</sup> (catalyst) h<sup>-1</sup>. In addition to being one order of magnitude more productive on a spacetime-yield basis, the continuous system is also more selective for caprolactone at these elevated productivities (70% vs. 39%), and more selective with the  $H_2O_2$  utilised, thus demonstrating the major advantages of the continuous system.

## **Experimental Section**

#### Catalyst synthesis and pre-treatment

Zeolite Al- $\beta$  (Zeolyst, NH<sub>4</sub>-form, SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>=38) was dealuminated by treatment in HNO<sub>3</sub> solution (13  $\mbox{M}$  HNO<sub>3</sub>, 100 °C, 20 h, 20 mLg<sup>-1</sup> zeolite). The dealuminated powder was washed with water and dried overnight at 110 °C. Solid-state stannation was performed by grinding the appropriate amount of tin(II) acetate with the necessary amount of dealuminated zeolite for 10 minutes in a pestle and mortar, prior to heat treatment in a combustion furnace (Carbolite MTF12/38/400). A two-stage heat treatment was employed: to 550 °C (10 °C min<sup>-1</sup> ramp rate) first in a flow of N<sub>2</sub> (3 h not including ramp period) and subsequently in air (3 h) for a total of 6 h plus heating and cooling periods. Gas flow rates of 60 mLmin<sup>-1</sup> were employed at all times. The sample was held horizontally in an alumina combustion boat (10 mL capacity), and a quartz tube was used to seal the sample environment.

#### Kinetic evaluation and analytical methods

Batch BVO reactions were performed in a 100 mL round-bottomed flask equipped with a water-free reflux condenser. The reaction temperature was controlled by immersion in a silicon oil bath. The vessel was charged with a solution of cyclohexanone in 1,4-dioxane (10 mL, 0.33 M), which also contained an internal standard (biphenyl, 0.01 м), and the appropriate amount of catalyst. The vessel was subsequently heated to the desired temperature (100°C internal temperature). The reaction was initiated by addition of an appropriate amount of  $H_2O_2$ , typically corresponding to a  $H_2O_2/$ ketone ratio of 1.5. The solution was stirred at 750 rpm with an oval magnetic stirrer bar. Aliquots of the reaction solution were taken periodically for analysis, and were centrifuged prior to injection into a GC (Agilent 7820, 25 m CP-Wax 52 CB). Reactants were quantified against a biphenyl internal standard. H<sub>2</sub>O<sub>2</sub> concentrations were determined by titration against Ce<sup>4+</sup>. Batch caprolactone hydrolysis reactions were performed by using the same procedure and reaction conditions as used for the BVO reaction, although cyclohexanone was replaced with caprolactone.

Continuous BVO reactions were performed in a home-made plug flow, stainless steel, tubular reactor. Reactant delivery (0.33 M CyO in 1,4-dioxane, H<sub>2</sub>O<sub>2</sub>/ketone 1.5 or 0.75) was performed by an HPLC pump. The catalyst (0.4 g) was mixed with a diluent material (SiC (particle size of 63–75  $\mu$ m), 1.6 g) to avoid back mixing and to minimise the pressure drop, and the bed was placed in between two plugs of guartz wool. The diluted catalyst was densely packed into a  $\frac{1}{4}$  inch stainless steel tube (4.1 mm ID), and a frit (0.5  $\mu$ m) was placed at the end of the bed to avoid any loss of material. A contact time of 9.75 min was typically employed. The reactor temperature was controlled by immersion in a thermostatted oil bath, and the pressure was controlled by means of a backpressure regulator. The reaction feed was identical to that used for batch reactions. Aliquots of the BVO reaction solutions were taken periodically from a sampling valve placed after the reactor, and were analysed in the same manner as the batch reactions.

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- [13] Flow rate = 0.16 mL min<sup>-1</sup>; [CyO] = 0.33 m; mass (Sn- $\beta$ ) = 400 mg; Sn loading = 2 wt%. Accordingly, 0.783 moles CyO/mole Sn passes through the column per minute. Over 180 h, this equals approximately 8456.4 turnovers in the column. At a steady-state conversion of 60% (approximate average over 180 h) this equals approximately 5074 turnovers.
- [14] a) Batch reactor. [CyO] = 0.33 m; volume = 10 mL; mass of Sn- $\beta$  = 200 mg; max. conversion = 91%; time = 6 h. b) Flow reactor. [CyO] = 0.33 m; flow rate = 0.16 mLmin<sup>-1</sup>; reactor volume: 1.56 mL; mass of Sn- $\beta$  = 400 mg; max. conversion = 65%.

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# **FULL PAPERS**

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## 

Selectivity and Lifetime Effects in Zeolite-Catalysed Baeyer–Villiger Oxidation Investigated in Batch and Continuous Flow



**Selectivity and lifetime effects:** The mechanistic and intensification aspects of the Baeyer–Villiger oxidation of cyclo-

hexanone to caprolactone are investigated under batch and continuous-flow regimes.