Investigation of Copper Catalysts for Propylene Epoxidation

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Investigation of Copper Catalysts for Propylene Epoxidation

by

Hayden Elise Fowler

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# Table of Contents

List of Figures ................................................................................................................. 3

Abstract ......................................................................................................................... 4

Acknowledgements ....................................................................................................... 5

Chapter 1: Introduction ............................................................................................... 6

Chapter 2: Literature Review ..................................................................................... 9

Chapter 3: Materials and Methods ........................................................................... 12

  3.1 Catalyst Preparation ............................................................................................ 12

  3.2 Catalytic Reaction .............................................................................................. 14

  3.3 Catalyst Characterization .................................................................................. 17

Chapter 4: Results and Discussion .......................................................................... 18

  4.1 XRD Characterization ...................................................................................... 18

  4.2 Catalytic Performance ...................................................................................... 19

    4.2.1 Effect of Temperature ................................................................................ 20

    4.2.2 Effect of Flow Rate ................................................................................... 20

    4.2.3 Effect of Reactant Ratios .......................................................................... 21

  4.3 Comparison with Lambert’s Work ..................................................................... 22

Chapter 5: Conclusion ............................................................................................... 24

References ................................................................................................................. 25

Appendix .................................................................................................................. 27
List of Figures

Figure 1: Reaction of Propylene with Oxygen to Give Propylene Oxide ........................................ 7
Figure 2: Equipment used for Catalyst Preparation........................................................................... 13
Figure 3: The Catalyst Testing System .............................................................................................. 15
Figure 4: X-ray Diffractometer ........................................................................................................ 17
Figure 5: XRD Spectra of Catalyst Before and After Reaction............................................................... 18
Figure 6: Catalyst Performance ........................................................................................................ 19
Figure 7: Comparison with Lambert.................................................................................................. 23
Figure 8: 5% O₂, 5% C₃H₆, 90% Ar, 50 sccm: Selectivity and Conversion ............................................. 27
Figure 9: 5% O₂, 5% C₃H₆, 90% Ar, 50 sccm: PO Formation Rate and Conversion......................... 28
Figure 10: 5% O₂, 5% C₃H₆, 90% Ar, 20 sccm: Selectivity and Conversion ........................................ 28
Figure 11: 5% O₂, 5% C₃H₆, 90% Ar, 20 sccm: PO Formation Rate and Conversion ...................... 28
Figure 12: 5% O₂, 10% C₃H₆, 85% Ar, 20 sccm: Selectivity and Conversion ....................................... 28
Figure 13: 5% O₂, 10% C₃H₆, 85% Ar, 20 sccm: PO Formation Rate and Conversion ................. 28
Abstract

The industry for propylene oxide (PO) is in need of a more efficient, environmentally-friendly method of PO production. This study is focused on optimizing conditions for the gas-phase epoxidation of propylene with molecular oxygen in a single step over Cu catalysts for use in future research involving Au-Cu bimetallic catalysts. To do this, a 5 wt% Cu/SiO₂ catalyst was prepared using incipient wetness impregnation and tested over a temperature range of 220-300°C, varying the flow rate and ratio of reactants. Lower total flow rates led to higher conversions, and using excess oxygen favored complete combustion of propylene to CO₂. As temperature was increased, conversion and CO₂ selectivity were increased, and PO selectivity was decreased. These conditions will be used to design future Au-Cu bimetallic catalyst testing parameters.
Acknowledgements

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Chapter 1: Introduction

Propylene oxide (PO) is a very highly-valued chemical intermediate, produced at a rate of 8 million tons per year with a price of $2500 per ton, making PO production a $20 billion industry [1]. PO is used to synthesize other chemicals and polymers, such as propylene glycols, polyurethane, and polyether polyols [2]. These chemicals are ultimately used in a variety of significant applications. For example, polyurethane foams are used in the automobile and housing industries, while polyester resins are used in construction and textiles. Propylene glycol is also used as an additive in drugs, cosmetics, and hydraulic fluids. PO makes it possible to create these materials.

All current industrial methods for producing PO occur in multiple steps in the liquid phase. This requires separation processes for retrieving PO from other reaction products. Because of this, the cost and energy requirements of production plants is greatly increased. The most popular industrial methods of PO production are the chlorohydrin and hydroperoxide coproduct processes, accounting for 91% of commercial PO production in total [3]. Both methods produce an excessive amount of unwanted byproducts. The chlorohydrin process uses chlorine, a very hazardous chemical [2]. Furthermore, one of the major side products is CaCl2 salts, produced at 2.2 tons per ton of PO.2 Toxic, chlorinated organic compounds are also produced [1]. This method is overwhelmingly wasteful and harmful to the environment [3]. The hydroperoxide coproduct process attempts to make use of byproducts rather than producing harmful waste by creating useful chemical coproducts [3]. However, the method and required chemical plants are very complex. Even with the usefulness of the coproducts, their production is much greater than demand, being
produced at two to three times the amount of PO. This causes a major mismatch between PO and coproduct demand, making this process difficult to optimize.

Industrial production of PO has major downfalls, including being wasteful, expensive, inefficient, and environmentally harmful. The PO industry and the environment would greatly benefit from a more efficient, environmentally-friendly method of PO production. One possible alternative is the gas-phase epoxidation of propylene by molecular oxygen in the presence of a catalyst, as shown in Figure 1 [3]. This method, occurring in a single step, would greatly lessen the amount of equipment needed in plants, resulting in lower costs and energy usage. Due to the greater efficiency, PO could be produced in larger amounts at lower prices, allowing for more PO production plants to open and for more jobs to be created. When the gas-phase reaction is optimized, the only byproduct is water, making this method non-wasteful and environmentally friendly. Therefore, optimizing this method for industrial use would improve, if not eliminate, all current problems seen in current industrial methods.

$$2\text{CH}_3\text{CH}=\text{CH}_2 + \text{O}_2 \xrightarrow{\text{Catalyst}} 2\text{(PO)}$$

**Figure 1:** The gas-phase epoxidation of propylene by oxygen to give propylene oxide is given by the reaction. The only byproduct of this reaction is water ($\text{H}_2\text{O}$).

Au-Cu bimetallic catalysts could be the answer to this alternative method of production. Bimetallic catalysts offer a promising method for combining the best qualities of two metal catalysts. Many investigations have been done using coinage metals, i.e. Au, Ag, and Cu, as the catalyst for this reaction [1, 4]. The current benchmark catalyst for this reaction is Au, reaching selectivity for PO near 100% [1]. However, the conversion of
propylene to PO is low, and Au is expensive. Evidence exists to suggest that Cu may provide better conversion than Au and a better selectivity than Ag [1, 5]. Compared with Au, non-precious metal Cu offers an inexpensive, earth-abundant alternative. However, the selectivity of the reaction for PO from Au is still superior. Therefore, it is of great interest to produce a bimetallic Au-Cu catalyst to increase the conversion of propylene while maintaining the high selectivity offered by Au alone.

Before beginning this research, it would be beneficial to fully understand the performance and behavior of Cu catalysts for the reaction. While Au catalysts are mostly understood, Cu catalysts may operate optimally at completely different conditions for this reaction. This may include a different temperature range, amount of copper present, flow rate of reactants, or even ratio of reactants present. A better understanding of how monometallic Cu catalysts work will provide greater insight when designing bimetallic Au-Cu catalysts later, especially when considering reaction conditions and relative amounts of each metal present.

The purpose of this study was to optimize the conditions for the reaction of propylene with molecular oxygen over Cu catalysts. This work was based on Lambert’s research on Cu catalysts for propylene epoxidation, and a comparison was done with Lambert’s work accordingly [6]. The conditions to be optimized were total flow rate of reactants, ratio of propylene to oxygen, and temperature. Furthermore, characterization was done on the catalyst in order to understand the function of Cu catalysts for the reaction. The data and conclusions obtained from this study will be used when designing future experiments involving the testing of Au-Cu bimetallic catalysts.
Chapter 2: Literature Review

In 2005, Lambert’s group created two copper catalysts, A and B, and assessed their performances for use in propylene epoxidation. Catalyst A was created by microemulsion method, and Catalyst B was created by incipient wetness impregnation (IWI). Lambert’s group expected Catalyst A to have a smaller particle size than Catalyst B. Furthermore, the loading of Cu in Catalyst A was 1 wt.%, while the loading of Cu in Catalyst B was 5 wt.%.

The results showed that Catalyst B performed worse than Catalyst A, potentially indicating that smaller, more dispersed copper particles are better for propylene epoxidation. Lambert’s group also concluded that propylene oxide selectivity was best at 225°C, just short of 60% for Catalyst A, and just short of 20% for Catalyst B. As the temperature increased, the selectivity for acrolein also increased. Lambert’s group proposed that this was due to Cu⁰ being the predominant species at lower temperatures, with Cu⁺ (Cu₂O) and Cu²⁺ (CuO) being the predominant species at higher temperatures. Therefore, Lambert’s group concluded that propylene epoxidation must be associated with Cu⁰.

Additionally, Lambert’s group ran the reaction without hydrogen and with hydrogen. It is well known that the epoxidation of propylene may also occur with hydrogen and oxygen in the presence of a catalyst. This is because the catalyst aids in the formation of hydrogen peroxide from oxygen and hydrogen, which easily oxidizes propylene to propylene oxide. While this mechanism is highly predominant for Au catalysts, it is not known to work with copper catalysts. Lambert’s work sought to confirm that hydrogen was not necessary for the reaction nor participated in the formation of hydrogen peroxide in the presence of Cu catalyst. From this, it was concluded that a hydrogen cofeed had no effect on the reaction, confirming the lack of hydrogen peroxide formation [6].
The work of this capstone looked to repeat the creation of Catalyst B and to further compare performance results with those achieved by Lambert. While this catalyst performed worse in Lambert’s work, the methods used were easier to replicate, and the loading of Cu in the catalyst was easy to control. To create Catalyst B, IWI was used on a SiO$_2$ support with Cu(NO$_3$)$_2$ as a precursor. This was dried in air for 10 hours at 120°C. The catalyst was crushed and sieved to give a grain size between 250-600 µm. The catalyst was then calcined in air for 4 hours at 300°C and reduced in hydrogen for 2 hours [6]. These methods are discussed in further detail in Chapter 3.

Other works involving Cu catalysts for propylene epoxidation also exist. In 2009, Li’s group created copper catalysts by homogeneous deposition precipitation method, with each catalyst having a different promoter. Li’s group also experimented with reducing agents, pretreating catalysts with O$_2$, N$_2$, and H$_2$ prior to reactions. From these experiments, it was concluded again that smaller particle size was beneficial to propylene epoxidation. Furthermore, pretreatment with H$_2$ was determined to be better than pretreatment with N$_2$, and pretreatment with O$_2$ did not work. Li’s group predicted that this was because pretreatment with O$_2$ caused Cu$^{2+}$ species, given that O$_2$ would act as an oxidizing agent. Pretreatment with N$_2$ caused Cu$^+$ species, and pretreatment with H$_2$ caused Cu$^0$ species. From this, it was concluded that Cu$^0$ was still preferable for propylene epoxidation, but Cu$^+$ also worked, and Cu$^{2+}$ did not work at all [7].

Other sources appear to confirm the results of these two sources, i.e. smaller particle size and Cu$^0$ species is best, while Cu$^+$ also works, but not as well. Duzenli et al showed that a copper particle size of less than 5 nm was ideal [8]. In 2014, Yang’s group created copper catalysts on SBA-15 support, reporting the particle size for the catalysts to
be 1 – 4 nm. The group also demonstrated that as temperature was increased, selectivity for propylene oxide decreased, and Cu$^{2+}$ became the predominant species over Cu$^+$ [9]. Yang’s group further suggested that Cu/SiO$_2$ catalysts favored formation of acrolein, an undesired byproduct, over PO. To combat this, the group promoted the Cu catalysts with Cs, which resulted in an increase of selectivity for PO. The cause of this was proposed to be the strong interactions between alkali metals and CuO$_x$ species, leading to a decrease in the particle size of CuO$_x$ [10]. Tuysuz et al also confirmed Cu catalysts’ favorability for acrolein formation, though it should be noted that acrolein formation was the primary goal of this work [11].

In conclusion, particle size and oxidation state play an important role on the performance of Cu catalysts for propylene epoxidation. Smaller particle size (< 5 nm) has been found to favor formation of PO, as well as an oxidation state of Cu$^0$. The reaction is complete by only adding oxygen, and the introduction of hydrogen does not form hydrogen peroxide for the reaction. From the literature, the most common support for Cu catalysts is SiO$_2$. It is also clear that acrolein is one of the predominant, unwanted byproducts of the reaction.
Chapter 3: Materials and Methods

3.1 Catalyst Preparation

A 5 wt% Cu/SiO$_2$ catalyst was prepared using incipient wetness impregnation (IWI) as called for by Lambert’s methods [6]. This method involves contacting a precursor solution, i.e. an aqueous solution containing the catalyst metal as a salt, to a support, in this case SiO$_2$. It is important that the solution is added to the support in an amount that correlates to the support’s pore volume, or the free volume of the pores in the support. This is done to ensure that the catalyst species are evenly distributed in the pores of the material, leading to better catalytic activity. This also allows precise control of the amount of catalyst species deposited on the support, since the concentration of that species can be varied to a certain amount per pore volume of the support.

The pore volume of the SiO$_2$ support was first found by gradually adding water to 1 g of SiO$_2$ via pipette. This was done until the SiO$_2$ became “wet,” resembling damp sand. The total volume of water added was taken as the pore volume for 1 g of SiO$_2$. The pore volume was determined to be approximately 1.7 mL/g of SiO$_2$. 3 g of 5 wt% Cu/SiO$_2$ catalyst was to be made, requiring 0.15 g of Cu and 2.85 g of SiO$_2$. For 2.85 g of SiO$_2$, a total pore volume of 4.8 mL was available. Cu(NO$_3$)$_2$·3H$_2$O (Sigma Aldrich, 61197) was used to create the precursor solution. To obtain 0.15 g of Cu, 0.57 g of Cu(NO$_3$)$_2$·3H$_2$O were needed. Therefore, the precursor solution was to contain a concentration of 0.118 g/mL of Cu(NO$_3$)$_2$·3H$_2$O.

100 mL of a Cu(NO$_3$)$_2$ precursor solution was created by dissolving 11.8 g of Cu(NO$_3$)$_2$·3H$_2$O in deionized water to give a 0.118 g Cu(NO$_3$)$_2$·3H$_2$O/mL solution. 4.845 mL of precursor solution was deposited onto 2.85 g of SiO$_2$ via pipette with constant stirring.
This was done to ensure even distribution of precursor species within the pores of the support. The catalyst was dried in static air at atmospheric pressure for 10 hours at 120°C in a Jeio Tech OV-11 Vacuum Oven, shown in Figure 2A. The catalyst was then calcined in flowing air (50 mL/min) at 300°C for 4 hours in a Thermo Scientific Lindberg Blue M tube furnace, shown in Figure 2B. Calcination involves the burning off of unwanted species with heat and oxygen exposure. Since a precursor solution was used, calcination was done to burn off unwanted NO₃ species, leaving only CuOₓ species for the catalyst. At this point, the catalyst was stored as a nanopowder for further use in reaction analysis.

![Figure 2: (A) The Jeio Tech OV-11 vacuum oven and (B) the Thermo Scientific Lindberg Blue M tube furnace used in preparation of the Cu catalyst are picture.](image)

Prior to reaction, the catalyst was pressed and sieved to a grain size of 180-250 µm and reduced in 5% H₂ in Ar (total flow: 25 mL/min) for 1 hour and at 300°C. The reduction of the Cu species in the catalyst was done to remove oxygen from the surface of the catalyst since the literature review indicated that Cu⁰ was the best oxidation state for this reaction.
3.2 Catalytic Reaction

The catalyst testing system is shown in Figure 3. The overall testing system, Figure 3A, includes a control panel, Figure 3B; a reaction furnace, Figure 3C; a packed-bed reaction vessel, Figure 3D; and a gas chromatograph, Figure 3E. The control panel allows for the operator to adjust the flow rates of each gas via mass flow controllers, the temperature of the furnace via temperature controller, and the location for the gases to be sent to via control valves. The gas mixture may be sent to the furnace for reaction, purged to a vent, or sent directly to the gas chromatograph. The furnace, controlled by the temperature controller located with the control panel, contains a glass tube in which catalyst is loaded to create a packed-bed reactor.

100 mg of catalyst was diluted by 1 g of quartz and loaded into a glass tube to create the packed-bed reactor. The reactor was placed into the furnace, and the flow rates of reactant and carrier gases were varied as desired. The catalyst was tested at the following conditions on a temperature range of 220-300°C:

(1) 5% O₂, 5% C₃H₆, balanced in Ar at a flow rate of 50 mL/min
(2) 5% O₂, 5% C₃H₆, balanced in Ar at a flow rate of 20 mL/min
(3) 5% O₂, 10% C₃H₆ balanced in Ar at a flow rate of 20 mL/min

These conditions were chosen to determine the effects of flow rate and reactant ratios on the performance of the catalyst for the reaction. For example, moving from case (1) to case (2) allowed for the difference between 50 mL/min and 20 mL/min of total flow rate to be compared while keeping the ratio of oxygen to propylene constant at 1:1.
Moving from case (2) to case (3) allowed for the total flow rate to be held constant at 20 mL/min and for the ratio of oxygen to propylene to be changed from 1:1 to 1:2, corresponding to a more stoichiometric ratio as shown in Figure 1.

Figure 3: (A) The catalyst testing system is composed of three major parts: (B) the control panel, (C,D) the reaction furnace, and (E) the gas chromatograph.
Finally, the HP 5890 Series II gas chromatograph was used to analyze the products of reaction leaving the furnace. The chromatograph outputs data in the form of peaks, whose locations correspond to a specific residence time within the chromatograph and sizes correspond to a relative amount of species present in the gas mixture. Each species has a different specific residence time, making gas chromatography an ideal way to identify the species and their relative amounts present in the gas mixture. The conversion of propylene and the selectivity of the reaction for PO were calculated as defined by equations (1) and (2).

\[
(1) \quad \text{Conversion} = 1 - \frac{\text{(Amount of propylene present after reaction)}}{\text{(Amount of propylene present before reaction)}}
\]

\[
(2) \quad \text{Selectivity} = \frac{\text{(Amount of PO present)}}{\text{(Amount of total products present)}}
\]

Relative amounts and residence times for each species were determined by using calibration values found before experimentation. These values were recalibrated weekly in order to ensure accurate measurements of species.
3.3 Catalyst Characterization

X-Ray diffraction (XRD) analysis was performed on the catalyst before and after reaction using a Rigaku MiniFlex 600 X-ray diffractometer. XRD allows for the identification of crystalline species present in the form of peaks occurring at specific diffraction angles. Depending on the species’ crystal lattice structure, the peak pattern differs for different materials. In this case, XRD was primarily used to identify the oxidation state of Cu species before and after reaction.

Figure 4: The Rigaku MiniFlex 600 X-ray diffractometer was used to identify the species present in the catalyst before and after reaction.
Chapter 4: Results and Discussion

4.1 XRD Characterization

The XRD spectra taken before reaction of propylene and oxygen to PO, shown in Figure 5, are consistent with SiO$_2$ and Cu$^0$. This indicates that Cu$^0$ is the only present oxidation state of Cu prior to reaction and that the copper species in the catalyst were completely reduced by H$_2$.

After the reaction, as shown in Figure 5, the spectrum changes significantly, indicating a change in present species. Upon further analysis, it was determined that the new peaks are consistent with the Cu$^+$ and Cu$^{2+}$ oxidation states. Copper is easily oxidized, and given that molecular oxygen was used as a reactant, these results were consistent with the literature [6, 9].

Figure 5: The XRD spectra before (−) and after (−) reaction are depicted.
4.2 Catalytic Performance

The observable products of reaction were PO, CO$_2$, acrolein, ethanal, and acetone. Of these, CO$_2$ and acrolein were major, and PO was of interest. These were the major products noted in the literature as well [5]. Due to the minimal amounts of ethanal and acetone being produced, these byproducts will not be discussed further in this report (for additional data, including for all byproducts, see the Appendix). The primary results are presented in Figure 6.

Figure 6: The main data of interest are (A) the selectivity of the reaction for PO, (B) the selectivity of the reaction for Acrolein, (C) the selectivity of the reaction for CO$_2$, and (D) the conversion of propylene to products.
4.2.1 Effect of Temperature

For each case tested, temperature has a major effect on the conversion of propylene and the selectivity for certain products of reaction. As shown in Figure 6A and 6B, as temperature is increased, the selectivity of the reaction for PO and acrolein is decreased significantly. The opposite is true for selectivity of the reaction for CO\(_2\), as it increases with increasing temperature, as shown in Figure 6C. Conversion also increases with increasing temperature, as shown in Figure 6D. However, the conversion curves for each case do not light off within this temperature range. This is in good agreement with Lambert’s work, in which conversion curves also do not light off within this temperature range [6].

From this data, it appears that at lower temperatures where PO selectivity is higher, conversion is very small, and vice versa. Higher temperatures drive the reaction towards combustion of propylene to generate more CO\(_2\). This effect is also present in the literature [6, 7, 10]. Therefore, this catalyst alone would not be suitable for propylene epoxidation. However, combining Cu with Au and operating at a higher temperature could potentially increase the conversion of reaction while maintaining high selectivity. Since the reaction with Au will differ, an optimal temperature range for the bimetallic catalyst will need to be found. This temperature range can serve as the maximum consideration of temperatures, assuming Au follows the same pattern of decreasing PO selectivity with increasing temperature.

4.2.2 Effect of Flow Rate

From Figure 6A, it is shown that PO selectivity decreases when the total flow rate is decreased from 50 mL/min to 20 mL/min while maintaining a 1:1 ratio of propylene to oxygen. However, the selectivity for CO\(_2\) and acrolein do not appear to be affected by the
decrease in flow rate. Conversion behaves opposite of PO selectivity, increasing when the total flow rate is decreased from 50 mL/min to 20 mL/min maintain a 1:1 propylene to oxygen ratio.

These trends can be explained by the residence time of reactants in the catalyst bed. A higher flow rate should give a lower residence time. Lower residence times may also mean less time for the reactants to be converted into products. By this logic, an increase in flow rate, resulting in a decrease in residence time, should result in a lower conversion, and vice versa for a decrease in flow rate. This is shown by the data in Figure 6.

4.2.3 Effect of Reactant Ratios

Figure 6A shows that changing the ratio of propylene to oxygen from 1:1 to 2:1 has a significant effect on the selectivity of the reaction to PO while maintaining a constant total flow rate of 20 mL/min. This is true for the entire temperature range. Likewise, from Figure 6C, the selectivity of the reaction to CO$_2$ is decreased with this change in ratio. Figure 6D does not indicate a major change in conversion with this ratio change within this temperature range. Figure 6B could show a slight increase in acrolein selectivity with this ratio change, but the effect does not appear to be major.

This phenomenon is best explained by the stoichiometry of the reaction, shown in Figure 1. This reaction shows a 2:1 ratio of propylene to oxygen to give PO. Figure 6A and 6C show that the change in ratio from 1:1 to 2:1 leads to an increase in PO and decrease in CO$_2$. This indicates that a more stoichiometric ratio of reactants favors partial oxidation of propylene to PO, while an excess of oxygen favors complete combustion of propylene to CO$_2$. 

A similar effect can be seen in literature: a decrease in the partial pressure of oxygen led to a decrease in CO₂ production [11]. However, in the case of this work, this resulted in more acrolein production, which was the reaction of interest. In this study, the selectivity towards acrolein is also increased when the ratio of propylene to oxygen is increased. Therefore, it can be concluded that partial oxidation to either acrolein or propylene is favored over complete combustion to CO₂ with more stoichiometric feeds.

4.3 Comparison with Lambert’s Work

The preparation of the 5 wt% Cu/SiO₂ catalyst by IWI was largely inspired by a similar catalyst prepared in Lambert’s work [6]. A comparison between the two catalyst performances with regards to the production of major products is shown in Figure 7. The trends of major product selectivity vs. temperature were similar for both catalysts. However, the amount of product formed in each case was drastically different, especially in the case of Acrolein and CO₂. The catalyst of this work produced significantly more CO₂, and CO₂ production increased much more rapidly earlier in the temperature range. Lambert’s catalyst produced much less CO₂ at a more linear relationship to temperature.

Furthermore, at 220°C, no CO₂ was detectable, and the selectivity for Acrolein was higher than that of Lambert’s. Once possible explanation for this is the limits of the gas chromatograph used in this experiment. CO₂ may have been present but not able to be detected. Otherwise, CO₂ production for this catalyst has a very strong dependence on temperature.
Overall, Lambert’s catalyst performs better for PO selectivity, while the catalyst of this work largely favors combustion to CO$_2$. Changing the ratio of propylene to oxygen helped to decrease this effect.

**Figure 7:** A comparison of the data from this work and Lambert’s work is given for the selectivity of major observed products. Both catalysts were prepared similarly and tested under similar conditions. The general trends for selectivity are the same for both works. However, this work’s catalyst has a greater selectivity for CO$_2$, especially as higher temperatures.

Overall, Lambert’s catalyst performs better for PO selectivity, while the catalyst of this work largely favors combustion to CO$_2$. Changing the ratio of propylene to oxygen helped to decrease this effect.
Chapter 5: Conclusion

The results of this study will provide a guideline for testing conditions of future Cu-containing catalysts, particularly Au-Cu bimetallic catalysts. The goal is to use Cu to increase propylene conversion while maintaining high selectivity for PO offered by Au. Therefore, from these results, decreasing flow rate and providing a stoichiometric ratio of reactants will be considered for future Cu catalyst testing. Using higher temperature will also be considered for increasing conversion. However, the reaction temperature will also be largely dependent on the reaction conditions needed for Au catalysts. In general, trends have been established for temperature, flow rate, and reactant ratios with respect to selectivity and conversion. Therefore, a baseline for adjustments for future catalyst testing has been established.

This work could be expanded further by examining the effects of changing other characteristics of the catalyst. For example, Cu loading can be varied to determine the optimum amount of Cu to add to the catalyst, or the effect of different supports may be observed. However, the present Cu catalyst does not perform well for propylene epoxidation, and further experimentation with monometallic Cu catalysts would likely yield similar performance as indicated here and by the literature. Therefore, the next phase of this work would likely benefit more by continuing with the design and testing of bimetallic Au-Cu catalysts.
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    Combinatorially Prepared Cu Catalysts Supported on High and Low Surface Area 


Appendix

Data not discussed in the main text of this capstone are presented here as deemed relevant by the author.

**Figure 8:** For a 1:1 ratio of oxygen to propylene at a total flow rate of 50 sccm in Ar, the selectivity for each product and the total conversion of propylene in the tested temperature range are given.
Figure 9: For a 1:1 ratio of oxygen to propylene at a total flow rate of 50 sccm in Ar, the total conversion of propylene and the formation rate of PO in the tested temperature range are given.
Figure 10: For a 1:1 ratio of oxygen to propylene at a total flow rate of 20 sccm in Ar, the selectivity for each product and the total conversion of propylene in the tested temperature range are given.
Figure 11: For a 1:1 ratio of oxygen to propylene at a total flow rate of 20 sccm in Ar, the total conversion of propylene and the formation rate of PO in the tested temperature range are given.
Figure 12: For a 1:2 ratio of oxygen to propylene at a total flow rate of 20 sccm in Ar, the selectivity for each product and the total conversion of propylene in the tested temperature range are given.
Figure 13: For a 1:2 ratio of oxygen to propylene at a total flow rate of 20 sccm in Ar, the total conversion of propylene and the formation rate of PO in the tested temperature range are given.