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Combinatorial Study of Oxidation Catalysts: Uncovering Synthesis-Structure-Activity Relationships

Kathleen B. Mingle
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Combinatorial Study of Oxidation Catalysts: Uncovering Synthesis-Structure-Activity Relationships

by

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Bachelor of Science
Clarkson University 2013

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ABSTRACT

High throughput experimentation (HTE) in catalysis has proven useful in expediting materials discovery via parallelized synthesis, characterization, and testing of candidate materials. However, even in a high-throughput manner, the combinatorial explosion of relevant parameters far exceeds our ability to study. To further complicate the problem, a large time investment and great deal of characterization is often required to build an in-depth understanding of catalytic materials. It follows that the field of heterogeneous catalysis is rich with examples of catalytic systems that have been developed using trial and error efforts for which a lot is known but context is lacking. Techniques such as statistical design methodology can be used together with HTE to address this by facilitating more efficient and meaningful exploration of large parameter space problems. In this work, three examples of oxidation catalysis are highlighted where design of experiments was successfully paired with HTE to aid the catalyst development process and uncover novel synthesis-structure-activity relationships. In addition, the preparation of polyacid functionalized gold nanomaterials for use in Alzheimer’s therapy will be discussed.

First, synthesis factors important in the one pot colloidal synthesis of cobalt oxide nanoparticles including surfactant type, heating regimen, reducing agent, and reagent concentrations were studied with a series of factorial designs. Factors were linked to structural parameters including grain size and morphology as well as CO oxidation activity parameters such as light off temperature and activation energy. Ultimately, experiments revealed that the density of catalytically active grain boundaries and structure of the CoOx intermediates were the most important factors in enhancing
the cobalt oxide reactivity and provided models to tune these variables using synthesis conditions.

Second, the optimization of the co-promoter space for Cu-Ag/α-Al₂O₃ catalzed ethylene epoxidation will be discussed, where an emphasis was placed on screening novel promoting materials and using factorial design to develop an understanding of how catalyst structure and promotional effects change with respect to promoter loading and impregnation sequence. It was found that the activity of the catalysts was sensitive to both the co-promoters used and the reactant feed composition which further experimentation revealed was linked to the Cu-Ag alloy behavior as well as the Ag particle size and morphology. Additional studies investigating the ethylene epoxidation activity of novel AgNP-Ag-LSX hybrid materials prepared with various post-synthetic modifications by collaborators will also be discussed.

The partial oxidation of ethane to acetic acid and ethylene will be discussed as a third application in oxidation catalysis. In this work, the structure and activity of doped Mo₈V₂Nb₁ mixed oxide catalysts were investigated. Specifically, the mixed oxide was doped with various redox (Pd,Ni,Ti) and acid (K,Te,Cs) elements at different redox:acid and dopant:host ratios; the effects of which were explored using a three-level, four-factor full factorial design. An emphasis was placed on understanding how the incorporation of various dopants affected the structure of the mixed metal oxide and the redox:acid dopant balance needed to achieve the desired specificity to various partial oxidation products.

In a slightly unrelated thrust, the development of polyacid functionalized gold nanoparticles and studies of their efficacy as Amyloid-β aggregation inhibitors in Alzheimer’s therapy will be discussed. The main focus of this work was leveraging existing polymer science and nanomaterials synthesis knowledge to establish on-demand control of the polymer length and nanoparticle size for the development of functionalized AuNP therapeutics. Additionally, the experimental efforts of the project col-
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List of Symbols

\( a \)  Pre-exponential factor in the Arrhenius expression

\( A \)  Absorbance

\( C \)  Concentration

\( e \)  Residual

\( E_a \)  Apparent activation energy

\( D \)  Diameter of nanoparticle

\( D_{TEM} \)  Diameter of nanoparticle as measured with TEM

\( D_{XRD} \)  Diameter of nanoparticle as measured with XRD

\( E \)  Expected value in statistical design

\( H_0 \)  Null hypothesis

\( H_1 \)  Alternative hypothesis

\( K \)  Shape factor

\( L \)  Path length

\( MS \)  Mean square of SS in statistical design

\( N \)  Degree of polymerization
\( n_E \) Number of elements

\( n_T \) Number of elements in each catalyst

\( P_i \) Partial pressure of component \( i \)

\( r \) Reaction rate

\( R \) Ideal gas constant

\( S \) Catalytic selectivity

\( SS \) Sum of squares

\( t \) Size of the coherently diffracting crystalline domain

\( X \) Catalytic conversion

\( y_{ij} \) The \( j \)th observation of factor level \( i \)

\( \beta \) Peak broadening at FWHM in XRD pattern

\( \beta_i \) Main effect coefficients

\( \beta_{ij} \) Interaction effect coefficients

\( \epsilon \) Molar absorptivity

\( \epsilon_{ij} \) Error in statistical design

\( \eta \) Degree of grain boundary consolidation

\( \theta \) Bragg angle
$\lambda$  Wavelength of the x-ray source

$\mu$  Overall mean

$\sigma$  Standard deviation

$\tau$  Treatment effect
<table>
<thead>
<tr>
<th>Abbreviation</th>
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<tbody>
<tr>
<td>AA</td>
<td>Acetic Acid</td>
</tr>
<tr>
<td>Ac</td>
<td>Acetate</td>
</tr>
<tr>
<td>$A\beta$</td>
<td>Amyloid-$\beta$</td>
</tr>
<tr>
<td>AD</td>
<td>Alzheimer’s Disease</td>
</tr>
<tr>
<td>AIBN</td>
<td>Azobisisobutyronitrile</td>
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<td>ANOVA</td>
<td>Analysis of Variance</td>
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<td>AuNP</td>
<td>Gold Nanoparticle</td>
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<tr>
<td>C/G</td>
<td>Citrate/Gold Molar Ratio</td>
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<td>CCD</td>
<td>Central Composite Design</td>
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<td>Deuterated Chloroform</td>
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<td>CTA</td>
<td>Chain Transfer Agent</td>
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<tr>
<td>CTAB</td>
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<tr>
<td>D/H</td>
<td>Dopant/Host Ratio</td>
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<tr>
<td>DCM</td>
<td>Dichloromethane</td>
</tr>
<tr>
<td>DFT</td>
<td>Density Functional Theory</td>
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<td>DIW</td>
<td>De-Ionized Water</td>
</tr>
<tr>
<td>DLS</td>
<td>Dynamic Light Scattering</td>
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DOE ................................................................. Design of Experiments

EDO ................................................................. Ethylenedioxy

EDS ................................................................. Energy Dispersive X-ray Spectroscopy

EO ................................................................. Ethylene Oxide

EPO ................................................................. Ethane Partial Oxidation

f-CoO ............................................................... fcc CoO

fcc ................................................................. Face Centered Cubic

FPA ................................................................. Focal Plane Array

FTIR ................................................................. Fourier Transform Infrared Spectroscopy

FWHM ................................................................. Full-Width-Half-Max

GC ................................................................. Gas Chromatography

GPA ................................................................. Gas Phase Array

GPC ................................................................. Gel Permeation Chromatography

h-CoO ............................................................... hcp CoO

hcp ................................................................. Hexagonal Close Packed

HREELS .......................................................... High-Resolution Electron Energy-Loss Spectroscopy

HRTEM ............................................................ High Resolution Transmission Electron Microscopy

HT ................................................................. High Throughput

HTE ................................................................. High Throughput Experimentation

HTR ................................................................. High Throughput Reactor
ICP-MS . . . . . . . . . . . . Inductively Coupled Plasma Mass Spectrometry
LEF . . . . . . . . . . . . . . Lag Extension Factor
LHS . . . . . . . . . . . . . . Layered Hydroxy Structure
LSX . . . . . . . . . . . . . . Low Silica Analogue of Faujasite
Mn . . . . . . . . . . . . . . Number Average Molecular Weight
Mw . . . . . . . . . . . . . . Weight Average Molecular Weight
NMR . . . . . . . . . . . . . Nuclear Magnetic Resonance
NP . . . . . . . . . . . . . . Nanoparticle
OA . . . . . . . . . . . . . . Oleic Acid
ODH . . . . . . . . . . . . . Oxidative Dehydrogenation
OFAT . . . . . . . . . . . . . One Factor at a Time
OME . . . . . . . . . . . . . Oxametallacycle
PAA . . . . . . . . . . . . . Polyacrylic Acid
PDI . . . . . . . . . . . . . Polydispersity Index
PPIR . . . . . . . . . . . . . Primary Phase Intensity Ratio
ptBA . . . . . . . . . . . . . Poly tert-Butyl Acrylate
PVP . . . . . . . . . . . . . Polyvinylpyrrolidone
R/A . . . . . . . . . . . . . Redox/Acid Ratio
RAFT . . . . . . . . . . . . Reversible Addition-Fragmentation Chain-Transfer
RSD . . . . . . . . . . . . . Response Surface Design
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>SCR</td>
<td>Selective Catalytic Reduction</td>
</tr>
<tr>
<td>SEC</td>
<td>Size Exclusion Chromatography</td>
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<tr>
<td>SEM</td>
<td>Scanning Electron Microscopy</td>
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<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>SPIR</td>
<td>Secondary Phase Intensity Ratio</td>
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<tr>
<td>tBA</td>
<td>tert-Butyl Acrylate</td>
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<tr>
<td>TCD</td>
<td>Thermal Conductivity Detector</td>
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<tr>
<td>TEA</td>
<td>Triethyl Amine</td>
</tr>
<tr>
<td>TEM</td>
<td>Transmission Electron Microscopy</td>
</tr>
<tr>
<td>TGA</td>
<td>Thermogravimetric Analysis</td>
</tr>
<tr>
<td>THF</td>
<td>Tetrahydrofuran</td>
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<tr>
<td>TPD</td>
<td>Temperature Programmed Desorption</td>
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<tr>
<td>TOAB</td>
<td>Tetraoctylammonium Bromide</td>
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<tr>
<td>UHV</td>
<td>Ultra-high Vacuum</td>
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<tr>
<td>UV-Vis</td>
<td>UV-Vis Spectroscopy</td>
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<tr>
<td>XPS</td>
<td>X-ray Photoelectron Spectroscopy</td>
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<td>XRD</td>
<td>X-ray Diffraction</td>
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CHAPTER 1

OVERVIEW

Many important industrial processes and almost all exhaust after-treatment technologies rely heavily on heterogeneous catalysis, in which catalytically active materials are used to accelerate the transformation of a starting material into a more valuable or less noxious chemical. Currently, most catalysis studies are focused on making incremental improvements to well-known issues or building fundamental knowledge around the catalyst surface. While these studies are important, they will not necessarily help us invent breakthrough catalytic materials or quickly adapt existing technologies to process changes or emerging environmental issues. This is largely due to the breadth and complexity of the parameter space needing to be explored. Multi-factor interactions can be discovered and quantified for use in predictive models through the methodical sampling of the design space. When paired with high throughput experimentation (HTE), this methodology can substantially expedite the discovery, development, and optimization process for environmentally and industrially important catalysts. [1] [2] [3] [4] [5] [6] [7]

1.1 HIGH-THROUGHPUT EXPERIMENTATION

The high throughput approach was first instated as a materials development tool in the mid-1990s, leveraging the success of the pharmaceutical industry a few years earlier [8]. Early on, high throughput studies in heterogeneous catalysis mostly relied on crude comparisons of qualitative data. For example, IR thermography was used by Moates et al in 1996 to screen an alumina supported metal combinatorial catalyst
library for hydrogen oxidation activity by detecting temperature variations on the catalyst surface arising from varying heats of reaction [9]. Since hydrogen oxidation is an exothermic reaction, catalysts of high IR signal were taken as the most active. Now, screening technology in high throughput catalysis has matured to the point where high quality quantitative information is obtained of comparable quality to that from a traditional single channel reactor. A number of diverse screening technologies are employed including FTIR, laser induced fluorescence imaging, cataluminescence, and resonance enhanced multiphoton ionization [6, 10–12]. Furthermore, complex reaction data such as the presence of surface active species, catalyst selectivity for a particular product, and kinetic parameters such as activation energy are easily and regularly measured with high throughput techniques [13, 14].

1.1.1 Material Discovery and Optimization

High throughput experimentation has proven useful in expediting materials discovery via parallelized synthesis, characterization, and testing of candidate materials. That being said, the efficacy of high throughput catalysis is limited by our ability to screen and optimize materials in an intelligent manner. The staggering complexity of the parameter space is best understood by considering the number of discrete combinations that arise from a set of independent variables. For example, a simple parameter space including combinations of 30 transition metals exceeds 1032 catalyst formulations [14]. This can be seen from Equation 1.1, where N is the total number of catalysts, n_E is the number of elements, and n_T is the number of elements in each catalyst.

\[
N\left(\frac{n_E}{n_T}\right) = \frac{n_E!}{n_T!(n_E - n_T)!}
\] (1.1)

It is useful to separate the high throughput process into three phases; library design, lead generation, and lead optimization. A number of methods exist which are
useful in aiding experimentation in each stage of this process. When employed intelligently, these methods help us to decipher quantitative structure-activity relationships in catalysis with minimal human effort. Most of these methods can be classified as either stochastic or deterministic in their approach. Both of these methodologies utilize heuristics to simplify the problem solving process but differ in their initialization; deterministic meaning a pre-defined and stochastic implying a randomly selected initial space. Of these methods, the most commonly used in high throughput analysis include design of experiments (DOE), artificial neural networks (ANN), genetic algorithms (GA), and monte carlo (MC) methods [15–18]. DoE related methodology serves to maximize the knowledge gained from a minimum set of experiments and is considered by many to be essential in planning and executing high throughput studies [19]. Many examples of the successful implementation of DOE in HT research exist, an example being the optimization of Nitrogen Storage and Reduction (NSR) catalysts [20]. Artificial neural networks are used to study input/output relationships by relying on training sets to resolve inner network dependencies. ANNs have been used to model kinetic reaction data in the hydroisomerization of n-paraffins, as well as in combination with GAs in the optimization of catalyst formulation for the oxidative dehydrogenation of propane to propene [20–22]. Genetic algorithms are loosely based on the rules of natural selection, where nth generation catalysts are formulated via crossover and mutation of their n-1th generation parents, thus facilitating the evolution toward an optimal solution. MC approaches function by subjecting catalyst formulation to random perturbations and associating probabilities based on the response, as demonstrated by Chen and Deem in the optimized synthesis of zeolites [23].

The majority of high throughput work in heterogeneous catalysis has classically been focused on optimizing catalyst formulation without emphasizing the surface chemistry and reaction mechanism involved. That being said, high throughput stud-
ies which provide definitive chemical explanations for observed results are achievable when paired with surface science (e.g. TPD, XPS) and reaction modeling (e.g. DFT, microkinetic) studies. Proper integration of these techniques, including that information which is available in the existing literature, can substantially improve the fundamental basis and impact of HTE. Examples involving this type of methodology include surface science motivated HT studies of ethylene epoxidation catalysts and the mechanistic study of ammonia decomposition on various catalysts via HT and microkinetic modeling [13, 14].

1.2 CO Oxidation over Cobalt Oxide Nanocatalysts

Colloidal synthesis of nanoparticles is a versatile approach used to prepare materials with drastically different properties, potentially allowing them to be tailored for a wide range of applications in medicine, catalysis, and more [24]. However, the difficulty in understanding relationships between synthesis conditions, desirable properties, and material performance is a limiting factor in the utility of these methods. An example of one such system are cobalt oxide nanoparticles. The properties of cobalt oxide nanomaterials, such as phase, morphology and crystal faceting are known to affect properties such as active site density and redox properties which are important for catalyst reactivity in various oxidation and hydrogenation reactions, but the accessibility of these features through nanoparticle synthesis is poorly established [25–33].

Cobalt and its oxides have a great deal of utility as precious metal replacements for numerous applications including CO and CO$_2$ hydrogenation [28, 34, 35], N$_2$O decomposition [36–38], CO oxidation [26, 39–41], and other total hydrocarbon oxidations [42–44]. Carbon monoxide (CO) is a toxic gas produced during the partial combustion of all carbon-based fuels. Numerous studies have been completed where CO is oxidized to CO$_2$ over varying materials including many noble metals, base
metals, and perovskites [45, 46]. A particular focus in the field has been placed upon developing high activity/low cost catalysts that light-off at low and even sub-zero temperatures. Despite the significant progress which has been made in reducing CO emissions in recent years, cold start emissions remain a challenge. To this end, base metal oxides have continually garnered attention due to their high activity and strong potential as low cost additives to traditional noble metal catalysts as well as being prospective catalysts for DeNOx processes and volatile organic compound (VOC) abatement from stationary sources [47].

Cobalt oxides demonstrate very interesting activity for CO oxidation, although they were originally passed over as catalytic converter materials due to their failure to perform under cyclic conditions and their susceptibility to sulfur and water poisoning. Now, an improved ability to synthesize metal oxides with desired properties and evolving fuel compositions (e.g. lower sulfur content) have made it practical to reassess such materials as emission abatement catalysts [47].

In addition to potential applications for novel CO oxidation catalysts in emission abatement technologies, the reaction remains heavily studied for academic purposes. CO oxidation is relatively simple and well understood—having been studied a great deal within the heterogeneous catalysis community, which makes it uniquely useful as a benchmarking and validation tool for many projects. To elaborate, CO oxidation activity serves as a baseline for comparison between different reactor systems and catalytic materials due to the simplicity of the reaction mechanism and the diversity of CO oxidation studies in literature. Presently, most researchers agree that CO oxidation on Co$_3$O$_4$ catalysts occurs via a Mars van Krevelen type mechanism where the active species is presumed to be Co$^{3+}$ and less frequently, Co$^{2+}$ [26, 48]. Because of this, CO oxidation is a useful probe reaction which can be used to glean structure sensitivities relevant to other reaction chemistries and for these reasons CO oxidation was investigated as a model reaction in a large part of this thesis.
When considering the rate of a catalytic reaction, there are certain variables in its kinetic equation, such as the surface concentration of active sites (part of the pre-exponential factor) and the activation energy of the reaction, that are material and/or structurally specific [49]. When a reaction is structure sensitive, these factors are subject to change when the catalyst size, shape, and morphology are tuned. For example, this could happen as a result of the exposure or occurrence of low coordination edge or defect sites.

The numerous shape, size, and structure sensitivities that have been reported for cobalt oxide nanocatalysts make them interesting materials to study. One such example is the ease at which Co$_3$O$_4$ can form electrophilic oxygen species (either O$^-$ or O$_2$$^-$), as indicated by the concentration of these species on the oxide surface. Miyamoto et al showed using rectangular NH$_3$ pulse techniques that the surface oxygen contents were different for Co$_3$O$_4$ formed through the thermal decomposition of cobalt (II) carbonate when compared to Co$_3$O$_4$ formed through the hydrolysis of cobalt (II) nitrate [50]. This work was elaborated on by the Cao group who showed that cobalt oxides prepared using a soft reactive grinding (SRG) procedure had very high propane total oxidation rates which correlated with high concentrations of superficial electrophilic oxygen (O$^-$) as evidenced by peak speciation in O$_2$-TPD results [42]. The same group suggested that enhanced stability and activity among certain samples could be further linked to increased surface defects created by long periods of grinding and evidenced by lattice distortion seen in XRD. Surface defects such as vacancies or steps and bulk extended defects such as dislocations, stacking faults, and twins are a reality of transition metal oxides which can potentially change the adsorption properties (eg. surface oxygen bond strength) and reactivity of the surfaces which they inhabit [51]. Work by Sadykov et al definitively linked cobalt oxide defect density, which they defined indirectly by measuring the amount of weakly bonded oxygen, with catalytic activity for CO oxidation by demonstrating a linear
dependence between the two when defect density was controlled via the preparation procedure [51].

The bulk oxygen mobility in cobalt oxide materials is another important property related to structure and catalytic reactivity [42, 52]. Potentially, for metal oxides involved in catalytic reactions with mechanisms which utilize their surface redox functionality, this variable could drastically affect reaction rates [47]. This is due to an enhanced ability of the metal oxide to resupply the surface reaction with lattice oxygen. In recent years, researchers have begun to recognize the sensitivity of this variable to factors such as grain boundary consolidation, where the coalescence of grains can increase oxygen diffusion rates from the bulk, among other favorable effects [49].

The surface enrichment of the Co\(^{3+}\) cation in Co\(_3\)O\(_4\) is perhaps the most heavily discussed cobalt oxide structure sensitivity in heterogeneous catalysis. Co\(_3\)O\(_4\) has a regular spinel structure which contains a mix of octahedrally coordinated Co\(^{3+}\) cations and tetrahedrally coordinated Co\(^{2+}\) cations. The relative amounts of these cation types on the surface of Co\(_3\)O\(_4\) nanoparticles can be tuned via the surface faceting of the nanoparticles and/or the degree of spinel inversion. Control over the Co\(_3\)O\(_4\) cation distribution has been the subject of a great deal of research, as Co\(^{3+}\) surface enrichment and control over the Co\(^{3+}\)/Co\(^{2+}\) ratio have been established to dramatically affect specific reaction rates, stabilities, and light-off temperatures for many catalytic applications [53–57].

These structure sensitivities are, in one form or another, a consequence of the preparation conditions and variables used in the preparation of the cobalt oxide catalyst. However, most works dedicated toward the understanding of these relationships are extremely restricted in scope and don’t consider the co-dependence of various synthesis variables and structural descriptors. Thus, only with careful experimental design where numerous variables of interest are simultaneously tracked is it possible to link
preparation conditions, catalyst structure, and performance. To this end, factors known to be linked to cobalt oxide size and structure within the colloidal synthesis family were screened to establish their importance on structural properties and build predictive models with which to tune these properties [58, 59]. A series of 2-level factorial designs and response surface designs were used throughout the project with the aim of discerning the roles of factors involved in the synthesis of cobalt oxide nanoparticles through the thermal decomposition of cobalt acetate with diols in dibenzyl ether and discovering their influence on nanoparticle properties (size, morphology, phase) and catalyst performance in CO oxidation.

1.3 Ethylene Epoxidation over Promoted and Cu Containing Ag/α-Al₂O₃ Catalysts

The selective oxidation of ethylene to ethylene oxide is one of the most important and profitable oxidation processes used in industry today, generating billions of U.S. dollars annually [60]. Ethylene oxide is a widely used intermediate in the production of valuable chemicals such as ethylene glycol and ethoxylates. 71.3% of ethylene oxide produced industrially is used to make glycols, an important chemical in the manufacturing of consumer products including polyester and antifreeze. The major challenge for any selective oxidation reaction is the prevention of total oxidation and the optimized yield of the selective product.

Since its commercialization by Union Carbide Co. in 1937 [61], our mechanistic understanding of Ag/α-Al₂O₃ catalyzed ethylene epoxidation has improved tremendously. As a result, selectivity toward ethylene oxide in industrial ethylene epoxidation has nearly doubled since its discovery. Prior to the 1990s, most research was focused on the reaction mechanism and origin of selectivity on silver catalysts. During this time it was first proposed that selectivity on Ag catalysts should be attributed to the nature of the Ag-O bond. A formal chemical explanation was surmised in van
Santen’s 1989 review, stating that the electrophilic nature of the adsorbed oxygen and
the weak nature of the Ag-O bond favored ethylene oxide selectivity by preventing
π-bond activation [62].

The following decade of research was successful in settling the long standing de-
bate over the form of oxygen (e.g. atomic vs. molecular) responsible for ethylene
oxide selectivity. Originally, molecular surface oxygen was thought to be responsible
for the partial oxidation of ethylene to EO while atomic oxygen led to the undesired
combustion product [60]. Popular opinion changed after a series of temperature pro-
grammed reaction (TPR) spectroscopy studies concluded in the early 1990s discovered
that atomic oxygen was responsible for the selective product [63]. Continued work led
to the conclusion that atomic oxygen was actually responsible for both products with
the pathway depending on the valence charge of the adsorbed oxygen; electrophilic
oxygen favors EO formation while nucleophilic oxygen aids in H abstraction from
\( \text{C}_2\text{H}_4^* \) and leads to the formation of combustion products [62]. Studies have shown
that electrophilic oxygen (\( O_e \)) can form on the catalyst surface either directly from
nucleophilic oxygen (\( O_n \)) or via near-surface oxygen.

In the early 2000s Barteau and Linic used combined experimental and computa-
tional methods to show that both acetaldehyde and EO arise from a common oxamet-
allacycle (OME) surface intermeddiate [64, 65]. This phenomenon was substantiated
with temperature programmed desorption (TPD) and high-resolution electron energy-
loss spectroscopy (HREELS) observations of Ag(111) after EO adsorption at various
temperatures. Correlation of TPD, HREELS, and DFT results indicated activated
EO ring opening above 250 K to form a stable surface intermediate, consistent with
an oxametallacycle, which reforms EO at 300 K in addition to water, ethylene, and
other minor products.

The simplified mechanism proposed by Barteau and coworkers for EO formation
via the OME intermediate over a standard Ag/\( \alpha \)-Al\(_2\)O\(_3\) catalyst is shown in Equa-
tions 1.2 through 1.5 [66]. In said mechanism, gas phase oxygen dissociatively adsorbs onto two unoccupied surface sites (denoted *) to form $2O^*$ on the catalyst surface. Following the adsorption of gas phase $C_2H_4$, the two adsorbed reactants form the aforementioned oxametallacycle intermediate (denoted $CH_2CH_2O^*$). The final step is the isomerization of $CH_2CH_2O^*$ through ring closure to form adsorbed EO and its desorption from the surface. A consequence of the proposed mechanism is that the stability of the oxametallacycle determines whether EO or acetaldehyde, which leads to combustion products, is formed from the intermediate.

$$O_2 + \ast \leftrightarrow 2O^*$$  \hspace{1cm} (1.2)

$$C_2H_4 + 2 \ast \leftrightarrow C_2H_4^*$$  \hspace{1cm} (1.3)

$$C_2H_4^* + O^* \leftrightarrow CH_2CH_2O^*$$  \hspace{1cm} (1.4)

$$CH_2CH_2O^* \leftrightarrow CH_2CH_2O + \ast$$  \hspace{1cm} (1.5)

Since Barteau’s founding work, the concept of a stable OME intermediate has become a central assumption in many continued epoxidation studies [5, 13, 64–68]. In particular, microkinetic modeling studies from Stoltze and coworkers have provided substantial experimental proof of the oxametallacycles existence under industrially realistic conditions [69, 70]. In their proposed mechanism, the surface combination of ethylene, adsorbed on nucleophilic surface oxide, and electrophilic oxygen proceeds through the oxametallacycle surface structure before EO formation. Although Barteau and Stolze define the catalyst active phase and active oxygen species differently, they arrive at similar conclusions in that the adsorption of atomic oxygen and the insertion of atomic oxygen into the C=C bond are feasible rate limiting steps.
Waugh and Hague rejected the notion that OME stability, rather than Ag-O bond strength, determines EO selectivity [71]. Ozbek and Van Santen suggested that a direct epoxidation E-R path is available at high oxygen coverages in addition to the OME mediated path [72]. This explanation is motivated by the observation where acetaldehyde activation energy is lower than OME activation energy, indicating that EO would not be formed via OME. Studies focused on the secondary oxidation of ethylene oxide on silver surfaces have made differing mechanistic insights. Acetaldehyde is generally accepted as a surface intermediate for combustion, and some studies have proposed that acetaldehyde formation is the rate limiting step in the combustion of ethylene on Ag surfaces [60].

Due to practical limitations, much of our current fundamental understanding of the ethylene epoxidation reaction and its relevant mechanistic details has been rationalized with highly theorized work. For instance, classic UHV surface science studies have thus far proved infeasible as a means to directly observe the ethylene epoxidation reaction. Instead, mechanistic insights have relied upon more workable UHV studies around reactants, products, and intermediates adsorbed on single crystals including ethylene, molecular oxygen, EO, water, carbon dioxide, acetaldehyde, subsurface oxygen, atomic oxygen, and oxametallacycles [73–75].

It follows that various mechanistic details remain inconclusive, such as the behavior of the surface active oxygen species and formation of reaction intermediates. In certain cases the UHV findings even contradict those from traditional catalytic studies, an example being the relative affinity of ethylene and oxygen for the Ag active sites [70]. In such instances, usable knowledge regarding ethylene epoxidation is convoluted by the diversity of both the methods and conclusions of various researchers. In order to resolve experimental discrepancies and create knowledge relevant to the industrial process, which is performed in the 1-3 MPa pressure range, further experimental studies are needed to align UHV observations of intermediates...
A number of promoters, gas feed additives, and second metals have been employed to increase the otherwise low (40-50%) ethylene oxide selectivity in ethylene epoxidation. Promoters and diluting agents may be introduced into the catalytic system during the catalyst preparation stage or later on, as a trace feed gas. Industrially, Ag catalysts are promoted with Cl, Cs, or Re and exhibit >85% selectivity toward ethylene oxide [60, 67]. Additionally, second metals (e.g. Au, Pd, Cu) and varying supports have been studied as possible ethylene epoxidation materials [5, 76–78].

Industrial ethylene epoxidation occurs on a base silver catalyst supported on an inert, low surface area/large pore support (0.1-3 m2/g BET surface area). While the support of choice is almost always $\alpha$-Al$_2$O$_3$, other supports have been used including silica, silicon carbide, zeolites, and other aluminum oxides [79–82]. Recently, patent literature has suggested that EO selectivity and catalyst stability can be enhanced by utilizing supports of bimodal pore size distribution, especially in the case of rhenium promoted Ag catalysts on $\alpha$-Al$_2$O$_3$ which has been modified or mixed with mullite [83, 84].

Promoting materials added to the base Ag/support have included chlorine, rhenium, titanium, cesium, and other alkali metals and alkaline earth metals. While there is no ubiquitous opinion in the literature on the effects of the Ag-O interaction and OME stability on EO selectivity, many compelling insights have been made in terms of the genesis of promotion via different materials in ethylene epoxidation. The most widely employed promoter in industrial ethylene epoxidation is chlorine, which is added to the feed gas at the ppm level as an organic halide. Varying explanations have been provided for chlorine’s promotional effect [71]. Early studies focused on a possible steric effect of chlorine, while more recent work has suggested that the promotional effect is electronic in origin [85, 86].

A commonality between many promotional materials is that an upper limit is
reached where adding larger amounts of the promoter species has a diminished return on selectivity. Considering the diversity of the mechanisms proposed for commonly studied promoters such as Cl, Re, and Cs, it is logical to assume that combinations of such promoters could possibly assuage the diminished returns seen in single promoter systems.

Cu containing epoxidation catalysts began to generate interest following the discovery by Lambert et al via UHV studies that the baseline selectivity of Cu actually exceeds that of Ag, but is eventually hindered by the formation of surface Cu₂O [87]. Soon after, a series of works from Barteau and coworkers demonstrated that Ag-Cu bimetallic have a synergistic effect on EO selectivity and conversion, the latter of which is an uncommon trend for Ag promoters. Similar trends were observed in studies involving Ag-Cu bimetallic promoted by Cl and Cs. Under the assumption of the OME intermediate, kinetic studies over the Ag-Cu alloy showed that the reaction rate is limited by the surface reaction of O and C=C under oxygen rich conditions but is limited by the dissociation of oxygen under ethylene rich conditions [66].

The concept of stable Ag-Cu alloys under reaction conditions were discredited in a DFT study from Piccinin and Nguyen that predicted that several Ag-Cu surface structures were more energetically favorable. Furthermore, they concluded that no single stable structure could be credited with the improved EO selectivity, that no single mechanism could be used to describe them, and that none of the stable structures led to OME formation [88]. In a subsequent DFT-atomistic thermodynamic study, the same authors suggested that the Cu-Ag material exists as Ag particles surrounded by thin CuO layers which adsorb high partial pressure or low temperature ethylene as ethylenedioxy (EDO) [78].

Recently, Jayamurthy et al reported a maximum EO selectivity of 29% on Cu and 5% Cu/Al₂O₃ catalysts that diminished with time to 1%. They were able to sustain selectivity by feeding alternating pulses of hydrogen and oxygen in ethylene
or by adjusting the oxygen partial pressure to 0.07, which presumably maintained the Cu(I) state [76]. Chongterdtoonskul et al measured >95% EO selectivity and 5% yield for an Ag-Sn-Cu supported on SrTiO3 prepared by a sol-gel route, suggesting that Sn promotion may stabilize metallic Cu. [81], [82] It should be noted that the same authors also reported unusually high selectivity (>98%) for a base Ag/α-Al2O3 catalyst of comparable metal loading and operating conditions. Thus, it is unclear whether this enhanced selectivity is a result of catalyst preparation conditions, composition, or activity testing procedures.

1.4 Ethane Partial Oxidation Over MoVNb Based Oxides

A great deal of research over the past several decades has been dedicated to the catalytic conversion of ethane into value added olefins and chemicals [89, 90]. Conversion of ethane into value added products goes through either ethane deoxyhydrogenation, whose main product is ethylene [91–93], or ethane partial oxidation, which produces various C2 compounds of increased value such as ethylene [94, 95] and acetic acid [96–100]. Acetic acid is primarily synthesized via the BP-Monsanto Cativa process which is a homogenously catalyzed methanol carbonylation process using Rh or Ir materials [101] which is undesirable due to the difficulties encountered with catalyst recovery and product separation. Additionally, the development of efficient heterogeneous catalysts for ethane conversion into its value added products, acetic acid and ethylene, is of interest due to the high abundance of low cost ethane from shale gas.

Presently, molybdenum and vanadium mixed oxides represent the state of the art heterogeneous catalytic material for the partial oxidation of short alkanes due to their ability to convert ethane into value added products such as acrylic acid and acetic acid [97, 100, 102–107]. In addition, elements such as niobium and antimony have been added to these Mo-V-O structures with the objective of increasing their structural stability and maintaining the desired Mo-V phase [98]. The stabilization of
the active Mo-V-M-O (M=Al, Co, Cr, Fe, and Bi) phase through interactions between
the molybdenum and M species resulting in the formation of a solid solution during
the hydrothermal treatment has been explored as a means of forming a uniform phase
[108]. Of stabilizing agents explored, Nb was found to be the most effective stabilizing
agent for the Mo-V-M-O structure resulting in the mitigation of phase segregation
and increased activity in both ethane partial oxidation [98, 105, 109] and ethane
oxidative dehydrogenation [107, 110].

In addition to studies focused on stabilizing the Mo-V-O catalyst, many recent
studies have been dedicated to improving the catalytic performance through the in-
corporation of promoters. Such promoters are typically either acid/base elements
such as tellurium [98, 103], calcium, potassium [111] or transition metals with vary-
ing redox properties such as palladium, nickel and titanium [91, 108, 109]. Optimal
loadings of acid/base elements are typically on the same order of magnitude as the
loading of niobium into the base catalyst, such as Mo₆V₂Te₁Oₓ and Mo₆V₂Sb₁Oₓ
[106], where the acid/base elements in this case were tellurium and antimony in place
of the niobium. Similarly, in cases where the both the niobium and an additional
acid/base element is present, their atomic ratio remains at approximately unity, such
as Mo₁V₀.₂₂Nb₀.₁₅Te₀.₂₃ [104, 111, 112]. Interestingly, the destabilization of the pri-
mary Mo-V-O phase does not necessarilly result in decreased catalytic activity for
EPO, possibly due to the formation of new active sites in lieu of the Mo-V-O phase.
One such example is the incorporation of small amounts of alkali metals such as
potassium or basic metals such as bismuth to MoVTebO [111]. Due to extensive
segregation of the crystalline structure of mixed oxide catalysts upon addition of
dopants, forming a clear correlation between catalyst structure, dopants and perfor-
mance is currently challenging when comparing varied literature.

Contrary to findings for acid-element doping, optimal loadings of redox elements
vary based on the reducibility of the metal. For example, incorporating noble met-
als such as palladium has been shown to dramatically affect catalytic activity to favor acetic acid production with the addition of only 0.0025 wt\% Pd metal to a Mo$_{0.61}$V$_{0.31}$Nb$_{0.08}$O$_x$/TiO$_2$ catalyst [102]. On the other hand, less reducible transition metals such as nickel and titanium appear to require higher loadings to impart a comparable effect on activity, where optimal ethylene production was achieved using a Ni$_{0.85}$Nb$_{0.15}$O$_x$ catalyst [113] and high acetic acid production was achieved using a Mo$_6$V$_2$Al$_1$Ti$_{0.50}$O$_x$ catalyst [114]. While the doping of acid/base elements into Mo-V-O structures has been addressed in depth in other works [115], a comprehensive understanding of how co-incorporating both reducible and acidic species at varying levels affects both catalytic activity and structure, specifically in terms of the required balance between reducibility and acidity, remains unclear.

The work in this thesis is focused on addressing the effects of adding acid and redox elements in various ratios to elucidate their coupled effects on both ethane partial oxidation and their structural properties to gain insight into the origins of enhanced activity. To guide this work, DOE was employed to screen a three level four factor ($3^4$) full factorial design space of distinct catalyst formulations based on doping a Mo$_8$V$_2$Nb$_1$ catalyst. A hydrothermal synthesis method was used to prepare the desired Mo-V-O mixed oxide crystalline structure. The parameters explored include: transition metal redox element (Pd, Ni, and Ti) doped, acid/base element (K, Cs, and Te) doped, the ratio between the redox and acid/base element (0.005, 0.5, and 1.0), and the total dopant added relative to the niobium content of the base catalyst (0.005, 0.5, and 1.0). By systematically adjusting the acidity and reducibility of the catalyst across a range of elemental combinations, we can draw statistically significant conclusions on the coupled effects of doping Mo$_8$V$_2$Nb$_1$ mixed-oxide catalysts with elements of varied redox and acid functionality on the catalytic performance in ethane partial oxidation and the corresponding changes in crystalline structure.
1.5 Inhibition of Amyloid-β Aggregation with Polyacid Functionalized Gold Nanoparticle Therapeutics

Alzheimer’s Disease is estimated to affect more than 40 million patients worldwide [116] making it the world’s most prevalent neurodegenerative disease. Compared to other leading causes of death in the United States such as heart disease, cancer and stroke, for which treatments have become more effective and the number of affected individuals has decreased, the outlook for AD is devastating [117] and numbers are expected to double over the next three decades as the general population reaches older age due to increased life expectancy [118].

It’s generally accepted that AD begins to affect the brain 20 or 30 years before the first signs of dementia, which means that the estimate of 40 million affected individuals is likely erroneously low [116]. These neurological state of the affected individual typically continues to worsen until the disease becomes fatal. However, long before mortality, the dementia and associated problems with memory and language make performing normal activities of daily living impossible for the individual and 24-hour care is required.

While AD has only garnered the fear of the general public in the last four decades or so [116], efforts in medical science and bioengineering to solve the problem that is Alzheimer’s have been ongoing for much longer. The insight that Amyloid could be related to the pathogenesis of the disease by George Glenner in 1984 has been increasingly supported by the field and field of evidence and has evolved into what is commonly known as the Amyloid Cascade hypothesis, which is now the guiding idea behind billions of dollars of scientific research.

Amyloid beta (Aβ) is a polypeptide fragment which is found in the cerebrospinal fluid after it has been cleaved from the amyloid precursor protein. While the polypeptide fragment resides in the brains of all healthy humans, Aβ can aggregate into larger hierarchical structures, the presence of which are linked to AD in afflicted individ-
Amyloid beta (Aβ) is a polypeptide fragment which is found in the cerebrospinal fluid after it has been cleaved from the amyloid precursor protein. While the polypeptide fragment resides in the brains of all healthy humans, Aβ can aggregate under certain conditions through combination or monomer addition into fibrils, the presence of which are linked to AD in afflicted individuals. It should be noted that while details regarding the exact structure and nature of these fibrils is still under debate, it is generally agreed that their deposition into the brain as amyloid plaques or aggregates is an etiological factor in AD. As such, agents which are capable of disrupting the aggregation of Aβ as it is described by the Amyloid Cascade hypothesis are of considerable interest in the field.

Numerous therapeutics including small molecules, peptides and nanomaterials have been investigated as potential AD treatments which would act through the disruption of Aβ aggregation [119, 120]. Of these, NPs featuring a variety of material cores and surface functionalizations have emerged as promising therapeutics due to their inhibition of the process, the specifics of which appear to be dependent on their physical properties [121]. Moreover, potential NP therapeutic agents have inhibited Aβ aggregation at substoichiometric concentrations which far exceed other therapeutics such as small molecules and peptides and is an attractive characteristic for the safe and efficient delivery of the therapeutic [122]. The dependence of Aβ aggregation inhibition on the NP physical properties is of particular interest as the size, shape and functionalization of NPs are tunable using modern methods but are poorly understood due to the diverse physical properties and distinct lack of a fundamental theory describing the relevant molecular mechanics.

In certain cases, researchers have hypothesized that the disruption of Aβ aggregation which coincides with a NP therapeutic is due to physical contact between the
NP and Aβ. This, however, is simply not possible at the substoichiometric ratios for which it has been observed. For example, recent work investigating the effect of AuNP nanosphere diameter (8-40 nm) and surface functionalization (electrostatically associated citrate, cetylammonium bromide, polyacrylic acid (PAA) and polyallylamine hydrochloride) on Aβ aggregation found that each factor had a significant effect on the aggregation process [121]. Specifically, it was found that a solution of PAA-functionalized AuNP at a ratio of 1:2,000,000 with respect to Aβ fully inhibited Aβ aggregation in the absence of NaCl. This suggests that the effect of the functional AuNPs on the aggregation process is through the modulation of local solvent conditions, rather than through physical interference. This study aims to build an understanding of how nanomaterial properties (AuNP diameter and PAA length) affect the Aβ aggregation process.
Chapter 2
Experimental Methodology

2.1 16-Channel High Throughput Reactor and FTIR Imaging System

2.1.1 FTIR Parallel Imaging

Two major advances in the past 20 years of FTIR instrumentation have enabled its use as a HT screening tool in heterogeneous catalysis. First, the incorporation of focal plane array (FPA) detectors introduced an instrumental multiplex advantage which was previously absent in conventional FTIR systems. This facilitated the simultaneous collection of spatial and spectral information limited only by the number of pixels on the FPA. [123]

Next, imaging FTIR data collection times were reduced by an order of magnitude by replacing the commonly used step-scan spectrometer with a rapid-scanning spectrometer. Step-scan spectrometers typically achieve adequate SNR by collecting several frames of light intensity information at each mirror retardation. These frames are then averaged to provide each interferogram point. In the rapid-scanning spectrometer scheme data is collected continuously over the range of mirror retardations and requires only a single frame per interferogram point. In this way, stabilizing time required for the mirror is avoided and the total acquisition time is reduced.[12, 124–127]

The asynchronous rapid-scan FTIR spectrometer and FPA set-up was first realized and demonstrated in the Jochen Lauterbach group as a viable parallel imaging technique for multi-channel reactors. [12, 124–127] The basic concept of applying
FTIR imaging to HT screening involves collecting thousands of interferograms simultaneously using the FPA detector, which decreases the time required to acquire an FTIR image significantly. For instance, a spectral image with 4 cm\(^{-1}\) spectral resolution and a spectral range of 1360 cm\(^{-1}\) can be collected in only 34 s. such an image will contain a total of 12,384 spectra, based on the 128x128 FPA detector.[125]

Since its development, the HT-FTIR system has facilitated numerous studies within the Lauterbach group. A notable example was the optimization and development of alumina supported Pt, Ba, and Fe containing NO\(_x\) storage and reduction catalysts over a wide parameter space including catalyst composition, feed composition, cycling conditions, and transition metal promoters. These studies led to the discovery of Co/Ba as a highly effective and noble metal free NOx storage catalyst.[3, 20, 128] Additional HT studies focused on the micro kinetics of ammonia decomposition [14], stability of small pore zeolites in the NH\(_3\)-SCR of NO\(_x\) [4], promotional effects for Ag catalyzed ethylene epoxidation [5, 129], and several others [130, 131]. The pioneering design in HT-FTIR screening has also influenced other researchers. For example, Kubanek and co-workers have improved the degree of parallelization and designed a 49 channel reactor implemented in a FPA-IR setup which has been applied to chemistries such as n-pentane hydroisomerization [132].

Overall, rapid-scanning FTIR imaging has proven to be an effective parallel characterization method as demonstrated by the diverse set of HT reaction studies carried out both inside and outside the Lauterbach group over the last decade. The technique has proven useful for the identification of both gaseous and liquid species in the mid-IR range as well as the quantification of gas phase concentrations in a univariate or multivariate manner. A major limitation of HT-FTIR is it’s applicability to only IR-active molecules and the increasing difficulty encountered when making both qualitative and quantitative determinations for spectra including complicated hydrocarbon chemistry.
2.1.2 Reactor Set-up

A 16 channel parallel plug flow high throughput reactor was designed to replace and improve upon a previous generation which is described in detail in the enclosed reference. [133] The second generation reactor marks several improvements over the predecessor, which was designed in a honeycomb block structure including an equal number of heater and reactor blocks. Namely, the new reactor was built to include a more efficient catalyst unloading and loading process involving a drill powered winch system, improved temperature control and an improved flow distribution system. In lieu of heating blocks, four ceramic radiant heaters (3 in ID, 6 in height) are used for the new design (Figure 2.1). Ceramic vestibules fit snuggly into the top and bottom of each furnace for optimum insulation of the heated area. Since channel temperatures are controlled in groups of four rather than 16, improved temperature distribution is achieved. Moreover, this set-up provides the flexibility of running four unique temperature profiles simultaneously without cross talk between reactor channels. Four on-off PID controllers are used to control the power delivered to each of the four furnaces, based on temperature readings from K-type thermocouples placed in the center of each furnace. An additional thermocouple is housed in each of the 16 catalysts beds to ensure the accuracy of the heating profiles and detect catalyst light-off temperature information. These temperatures are displayed on an in-house developed LabView program alongside the 16 measured catalyst bed temperatures.

The 16-channel reactor apparatus, shown in Figure 2.2, features a stationary bottom plate and a moving top plate, which can be lifted with a small winch system to quickly load and unload catalysts. Typically, reactor tubes are preloaded with catalyst amounts between 50 and 500 mg of powdered catalyst supported on stainless steel frits. Once loaded, the movable top plate is then lowered to meet the reactor tubes. Flow is distributed between the 16 channels using a network of concentric capillary spirals stemming from a central inlet line all contained inside a heated box.
The outlets of this capillary box serve as the inlets to the 16 parallel fixed bed reactors. For clarity, the heated areas and additional 15 reactor channels are not included in Figure 2.2.

Temperature and flow distribution over the sixteen channels are compared in Figures 2.3 and 2.4. Effluent channel flow rates were measured at the exit of the high throughput reactor system and parallel FTIR measurement set-up to be on average, 26.8±1.9 ccm for the 16 channels with a range of 24.8-29.6 ccm when the inlet flow was configured to feed each channel 25 ccm of N\textsubscript{2}. Figure 2.4 shows the heating profile of the 16 channels when LabView is configured to heat all channels to 100 °C. As shown, heating from 25-100°C required 30 minutes to reach the prescribed temperature and stabilize. The average temperature over the 16 channels was 102.8±1.6°C with a range of 100.1-104.3°C.
2.1.3 Gas Phase Array Sampling Accessory

The HT-FTIR experimental set up (Figure 2.5) is comprised of a Bruker Equinox 55 FTIR spectrometer, a 128x128 pixel mercury cadmium telluride FPA detector (Santa Barbara Focalplane, Goleta, CA, USA) operated a 1610 Hz, sensitive from 4000-1000 cm$^{-1}$. Spectra are typically taken with 8 cm$^{-1}$ spectral resolution. A set of refractive optical elements were paired with an in-house developed gas phase array (GPA) sampling accessory.[134] Further details can be found in the following references.[124],[125],[12],[126] Optical elements include a gold plated front surface mirror, two ZnSe meniscus lenses for beam spreading and two plano convex BaF$_2$ lenses for beam collimation. Between the two sets of lenses, the beam travels through the GPA sampling accessory comprised of a bundle of 16 stainless steel tubes (3/8 in OD). Each end of the GPA is capped with 50x3 mm ZnSe windows sealed with
o-rings. The effluent gases from 16 reactor channels enter and exit the GPA through 1/8 in tubing welded to the GPA tubes.

2.1.4 Data Processing

Data acquisition is controlled via an in-house written software named JAIMP (Just Another Image Processor). Each interferogram contains 3554 data points. The data collection process for one spectral image containing 128x128 interferograms at a focal plane array frame rate of 1610 Hz takes approximately 2s. In order to improve the SNR, typically 32 interferograms are collected and averaged in under a minute. Subsequent data processing including the elimination of bad pixels and the Fourier
Figure 2.4: Temperature distribution over 16 channels in HTR (set point = 25 ccm)

Figure 2.5: Gas Phase Array Sampling Accessory
transform of the signal is performed using an in-house developed software package [134]. Quantitative analysis of the resultant multichannel IR spectra proceeds analogously to that of traditional IR and can be performed in a matter of seconds using GRAMS/AI calibration and prediction software to yield effluent gas phase concentrations.

2.1.5 Validation of 16-Channel Reactor System

A preliminary CO oxidation benchmark study was completed to quantify the overall measurement error associated with the newly constructed 16-channel apparatus. 2% CO and 5% O$_2$ balanced with N$_2$ was injected into each channel at a target space velocity of 60,000 mL-h$^{-1}$-gcat$^{-1}$ over a temperature ramp of 100-300$^\circ$C. Each channel, with the exception of a single channel which was kept empty for reference, was loaded with 100 mg of commercial 1% Pd/Al$_2$O$_3$ catalyst (Alfa Aesar). Both flow and temperature distributions were uniform across the 16 channels with relative standard errors of $\pm$1.3% and $\pm$0.7%, respectively. Above 200$^\circ$C, all Pd/Al$_2$O$_3$ containing channels showed uniform conversions with a relative standard error of $\pm$3.5%. All standard errors were calculated based on a 95% confidence interval. The CO conversion versus catalyst bed temperature data for each channel is shown in Figure 2.6. The highest errors between channels can be seen at lower temperature and lower conversions which is likely a result of the smaller CO$_2$ IR peak being integrated for the concentration prediction.

2.2 Design of Experiments (DOE)

Edisonian experimentation, or the so called one-factor-at-a-time (OFAT) approach to experimental design is at the foundation of science. Conducting experiments in this manner is both simple in the conceptualization of the study as well as the rigor of the analysis. Unfortuantely, realistic systems are rarely well described by OFAT studies
as a multitude of variables are usually important and interactions between various factors should not be overlooked. Additionally, for virtually any experiment where more than a single factor is of interest, factorial designs offer higher experimental efficiency with absolutely no loss in precision when compared to the OFAT counterpart. Furthermore, efficiency increases with the number of factors being considered. For example, a 2-factor design is 1.5 times more efficient than a comparable OFAT set of experiments and a 6-factor design is 3.5 times more efficient. Thus, when multiple factors are of interest it almost always makes sense to employ factorial experiments [135]. Successful examples of the implementation of DOE in catalyst research and further discussion of using DOE as a tool to explore quantitative-structure-activity-relationships (QSARs) in high-throughput experimentation can be found in the following references [3, 8, 39, 136–141]. For more details on the derivation of statistical equations and the DOE
Figure 2.7: Flow chart for approach to experimentation with DOE

process the reader is referred to the following introductory references, which were consulted heavily in the development of this section of the thesis [135, 142]. A typical procession through the DOE process, as it was carried out in this thesis, is shown in Figure 2.7.

2.2.1 ANOVA and Model Fitting

Analysis of Variance (ANOVA)

Analysis of Variance (ANOVA) refers to a family of methodologies used to statistically test for equality between group means which are populated by averaging a number of repeat observations at different levels of a variable. Essentially, ANOVA is testing the hypothesis that the different treatment means investigated are equivalent in their effect on the response of interest. A requirement of accurate analysis of data through ANOVA is that the observations made can be described by an effects model of the general form shown in Equation 2.1.

\[ y_{ij} = \mu + \tau_i + \epsilon_{ij} \]  

In Equation 2.1, \( y_{ij} \) is the \( j \)th observation made for factor level \( i \), \( \mu \) is the overall
mean including all treatment levels, \( \tau_i \) is the effect of the \( i \)th treatment and \( \epsilon_{ij} \) is the random error arising from all additional and unintentional sources relevant to the measurement. It should be noted that in this form, Equation 2.1 is actually a one-way analysis of variance model as only one factor is being investigated. Extension of the ANOVA model to the comparison of means arising from multiple factors is a routine practice in the analysis of factorial and response surface designs. Moreover, a distinction must also be made between an ANOVA on fixed versus random factors. Since factorial and response surface designs involve the deliberate and discrete selection of treatment levels, a discussion of fixed effect ANOVA models will be sufficient. Details on ANOVA for random factors is elaborated on in the following reference. [135].

In general, a one-way ANOVA for a fixed effects model is a test of the equality of a treatment means, \( \mu_i \) or treatment effects, \( \tau_i \) for the response of interest. The null and alternative hypotheses for the latter are shown in Equations 2.2 and 2.3.

\[
H_0 : \tau_1 = \tau_2 = \cdots \tau_a = 0 \quad (2.2)
\]

\[
H_1 : \tau_i \neq 0, \text{ for at least one } i \quad (2.3)
\]

This is accomplished by quite literally breaking down and comparing the individual components of variability in the observed results by writing the total corrected sum of squares, \( SS_T \) as the sum of squares of the differences between treatment averages and the overall average, \( SS_{Treatments} \), combined with the sum of squares of the differences between multiple observations of the same treatment and the overall average, \( SS_E \) as shown in Equation 2.4. For simplicity, this can be expressed as shown in Equation 2.5.

\[
\sum_{i=1}^{a} \sum_{j=1}^{n} (y_{ij} - \bar{y}_{.})^2 = n \sum_{i=1}^{a} (\bar{y}_i - \bar{y}_{..})^2 + \sum_{i=1}^{a} \sum_{j=1}^{n} (y_{ij} - \bar{y}_i)^2 \quad (2.4)
\]
Thus, the ANOVA identity shows that the total variance is equivalent to the combination of variance between treatments and variance within treatments and simply comparing the two sources of variance provides intuitive information on the system under study. Specifically, a larger disparity between the values of $SS_E$ and $SS_{Treatments}$ implies that the treatment means are different. The two sum of squares can be compared mathematically by first defining the mean squares of $SS_E$ and $SS_{Treatments}$ in Equations 2.6 and 2.7.

\[
MS_{Treatments} = \frac{SS_{Treatments}}{a - 1} \quad (2.6)
\]

\[
MS_E = \frac{SS_E}{N - a} \quad (2.7)
\]

Subsequently, simplified expressions for expected values (i.e., the long run averaged value) of $MS_E$ and $MS_{Treatments}$ may be arrived at by substituting the original effects model shown in Equation 2.1 and simplifying the resultant equations. The simplified expressions are shown in 2.8 and 2.9, respectively. Through examination, it is apparent that for equal treatment means, $MS_E = MS_{Treatments} = \sigma^2$ and that for different treatment means, $MS_{Treatments} > \sigma^2$.

\[
E(MS_E) = \sigma^2 \quad (2.8)
\]

\[
E(MS_{Treatments}) = \sigma^2 + \frac{n \sum_{i=1}^{a} \tau_i^2}{a - 1} \quad (2.9)
\]

A test of the hypothesis of no differences in treatment means as shown in Equations 2.2 and 2.3 can be carried out to make the evaluation formally. $SS_E/\sigma^2$ and
$SS_{Treatments}/\sigma^2$ can be considered independent chi-squared random variables according to Cochran’s Theorem because their combined degrees of freedom sum to the total degrees of freedom, $N-1$. The test statistic for the null hypothesis in Equation 2.2 is shown in Equation 2.10.

$$F_0 = \frac{SS_{Treatments}/(a-1)}{SS_E/(N-a)} = \frac{MS_{Treatments}}{MS_E}$$

If the null hypothesis that there is no difference in treatment means is true, $F_0$ will be an F distribution with $a-1$ and $N-a$ degrees of freedom. Conversely, $H_0$ should be rejected when $F_0 > F_{a,a-1,N-a}$, where $\alpha$ is related to the confidence level (ie. $\alpha=0.05$ for a 95% confidence interval). This is commonly referred to as an F-test. Percentage points for the F-distribution can be found in virtually all statistics textbooks including [135] and can also be used to assign $P$-values and conduct a $P$-test.

**Model Fitting**

Using the information gleaned from the ANOVA of the possible model terms it is possible to fit a model of the form presented in Equation 2.1 and establish confidence intervals. Completing this process for a single-factor model is discussed in detail in the aforementioned reference [135]. Here, discussion will be limited to fitting a fixed effects model in the context of factorial and response surface designs as well as ensuring model adequacy by checking the residuals. As an example, the model adequacy checks relevant to the analysis of MoVNb grain sizes presented later in this thesis will be highlighted.

**Model Adequacy Checking**

In practice, the interpretation from ANOVA is meaningless if the model, Equation 2.1 does not fit the data adequately. An adequate model is one where the residuals are structureless, normally and independently distributed and have constant variance.
\( \sigma^2 \) at all factor levels of investigated. The \( j \)th observation of the \( i \)th treatment are associated with a residual as defined in Equation 2.11. In this context, \( \hat{y}_{ij} \) is the value predicted by the model for the corresponding observation \( y_{ij} \).

\[
e_{ij} = y_{ij} - \hat{y}_{ij}
\]  

(2.11)

It is possible to check the normality of the residuals graphically, as is shown in the histogram of the residuals in Figure 2.8. In this case, normally distributed data would be symmetric and unimodal indicating the absence of skewness or multiple population means. An additional useful graphical technique for evaluating the normality of the residuals is with a normal probability plot such as that shown in Figure 2.9. This methodology was developed by Chambers in 1983 and involves plotting experimental residuals against a theoretical normal distribution for the purpose of comparison. In this analysis, deviations from a straight line are equivalent to deviations from an underlying normal distribution. It should be noted that deviations from a straight line in the center of the plot should be treated with more seriousness than deviations at the extreme low and high values as they can more significantly impact the F-test.

An additional requirement of structureless residuals is the absence of obvious trends with respect to fitted value. For example, a poor model may be one which tends to overpredict and yield higher residuals at higher predicted values. Checking for this type of undesirable behavior can be accomplished by examining a plot of residuals versus fitted value such as that shown in Figure 2.10. Here, the data should exhibit a random scatter with no obvious trend with respect to fitted value. If this requirement is met it suggests that the residuals are structureless with a constant variance \( \sigma^2 \) at all factor levels investigated.

In a similar manner, one can examine a plot of residuals versus observation order or time. An example of this analysis is shown in Figure 2.11. Much like the aforementioned interpretation of the residuals versus fitted value plot, the data should
Figure 2.8: Histogram of the residuals (response: MoVNb grain size, nm)

Figure 2.9: Normal probability plot of residuals (response: MoVNb grain size, nm)
Figure 2.10: Plot of residuals versus fitted values (response: MoVNb grain size, nm) exhibit a random scatter with respect to observation order indicating that important experimental parameters were not changing and causing drift within the data set. In fact, this type of graphical analysis may be useful to complete with virtually any additional data that has been collected which could possibly incur a change in the response of interest.

For models where the residuals are not already normally distributed it is often possible to perform variance stabilizing transformations. Practically, this entails applying a function to the entire data set which lessens or removes the dependence between \( \mu \) and \( \sigma^2 \). Depending on the initial relationship between \( \mu \) and \( \sigma^2 \) evident from the raw analysis one can choose a suitable transformation. Common transformations include square root, log, reciprocal square root, and reciprocal. While the determination of an ideal transformation can usually be accomplished through graphical examination of the residuals, as previously discussed, it is also possible to make the determination empirically. This is discussed in more detail in the following reference [135].

An additional topic of importance when discussing design of experiments, ANOVA
and model fitting is the quandary of outliers. In reality, the data points which appear to be outliers are often both the data points which are most interesting from a process improvement or optimization stand-point as well as the data points which lead to pause when performing model adequacy checks. Seemingly, there is no catch-all with how to handle these data points and multiple analyses are often needed to fully understand the data set. Futhermore, both statistical and non-statistical evidence are desirable to determine how to handle the supposed outlier. For example, a careful re-consideration of the experimental conditions surrounding the supposed outlier can be useful to determine its likelihood. Perhaps there is an interesting scientific explanation which could justify the existence of this point. Completing repeat measurements of the suspect and implementing a statistical outlier test such as Grubbs test may also be useful to this end.
2.2.2 Full and Fractional Factorial Designs

Both full and fractional factorial designs are potential candidates in the design of experiments once an initial parameter screening space has been selected. Typically, factorial designs are completed in $2^n$ experimental points where $n$ is the number of parameters and 2 is the number of levels. The arrangement of a 3-factor, 2-level full factorial design is shown graphically in Figure 2.12, where the eight gray circles represent the 8 experimental points which comprise the design. It is common practice to complete multiple replicates of a full design to lower error when the cost of experimentation allows.

It is possible to carry out only a fraction of a full factorial design, which is duly referred to as a fractional factorial design, comprised of $2^{n-k}$ experimental points, where $n$ is the number of parameters, 2 is the number of levels, and $k$ corresponds to the number of independent generators in the design. For example, a $2^{n-k}$ design with $k$ generators would be the $1/2^k$ fraction of a $2^n$ design. The number of generators used in a fractional factorial design determines how many terms will be aliased with one another (i.e. mathematically indistinguishable), ultimately fixing the resolution of the design. It is general practice to minimize the experimental expense in terms of time and cost while maximizing the resolution. Once a fraction of a full design has been completed it is a routine matter to fold-over the design into larger fractions when desired. This is discussed in detail in the aforementioned references [135, 142].

The first step in the analysis of a two-factor fractional or full factorial design involves calculating main and interaction effects, as shown in Equations 2.12 and 2.13 for a $2^2$ full factorial design for factors A and B. Specifically, main effects are defined as the response change with respect to a single factor when averaged over all levels of all other factors (2.12), while interaction effects are defined as the averaged difference in response with respect to a single factor at the low and high levels of the other factor [135].
Figure 2.12: Experimental configuration of a 3-factor, 2-level factorial design without center points

\[ A = \frac{1}{2n} ([ab - b] + [a - 1]) \] (2.12)

\[ AB = \frac{1}{2n} ([ab - b] - [a - 1]) \] (2.13)

The statistical importance of each main and interaction effect is then established using the ANOVA methodology, as previously discussed. This facilitates the determination of which effects should be included in a response surface model describing the system of interest. Such models are quite useful in the analysis of experimental data via factorial design due to the ease of viewing response space trends and interaction effects which are equivalent to curvature in the response surface.

In place of the effects model presented previously in Equation 2.1 it is possible to use a least squares approach to fit a regression model of the form shown in Equation 2.14. Here, \( y \) is the response of interest, \( \beta_i \) are the main effect coefficients approximated with least-squares, \( \beta_{ij} \) are the interaction effect coefficients approxi-
mated with least-squares, $\epsilon$ is the error, and $x_i$ are placeholder variables for factors A, B, and so on.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_{12} + \epsilon \quad (2.14)$$

A suitable model is generally one which includes all the statistically significant model terms as well as any terms necessary to keep the model hierarchal, meaning that a model with the term AB must also include the single factor terms A and B. Moreover, the residuals of this model should be normally distributed and free of time and order dependent behavior.

2.2.3 Response Surface Designs

In many cases, a screening design will reveal that higher order interactions are highly important in the prediction of a response of interest. In this type of situation, it is usually useful to complete a response surface design (RSD) to build a more accurate predictive model of the parameter space and incorporate terms which describe a non-linear response with respect to a single independent variable. The arrangement of a 2-factor central composite response surface design is shown graphically in Figure 2.13 where the inclusion of a center point (to be repeated multiple times) and axial points distinguish this design from that shown in Figure 2.12 illustrating a factorial design.

RSDs are differentiated from factorial designs by their higher density of experimental points and necessary replicates which provide an internal estimate of error and a model which includes all possible second order terms, as shown in Equation 2.15. Aside from these differences, the analysis of RSD experiments proceeds in an analogous fashion to factorial experiments where main effects and interaction effects are calculated, ANOVA is completed, a model is fitting using a least squares approach, and the model is checked for adequacy.
2.3 CATALYST SYNTHESIS METHODOLOGY

Several different methodologies were employed to synthesize metal and metal oxide catalysts, both supported and unsupported, in the projects outlined in this thesis. Specifically, a colloidal synthesis method involving the thermal reduction of cobalt acetate was used to prepare cobalt oxide nanocatalysts for CO oxidation, a wet impregnation method was used to prepare Ag and promoted Cu-Ag catalysts supported on low surface area $\alpha$-Al$_2$O$_3$ supports for ethylene epoxidation, and a hydrothermal synthesis method was used to prepare Pd,Ni,Ti,K,Cs,Te-doped MoVNb mixed oxide catalysts for the partial oxidation of ethane.
2.3.1 Colloidal Synthesis

A one pot colloidal synthesis technique was used to synthesize cobalt oxide nanoparticles with varied shape, size, and phase. Synthesis methodology was adapted from that reported in the following references [58, 59]. Specifically, cobalt acetate was thermally decomposed in a high boiling point solvent (dibenzyl ether) and reduced with a polyol (1,2-dodecanediol). Both polyvinylpyrrolidone (PVP) and oleic acid (OA) were investigated as capping agents to modulate nanoparticle growth by preventing excessive Oswald ripening. The relative concentrations of these reagents together with the temperature ramp and aging temperature of the reaction mixture comprised the parameters investigated using statistical design of experiments. A thermocouple submerged in the nanoparticle solution was used as an input to a PID temperature control system interfacing with a heating mantle. Thermal aging was carried out in a reflux apparatus under a constant purge of N\textsubscript{2} gas. After the reaction mixture cooled to room temperature the nanoparticles were precipitated using repetitive centrifugation and washed with acetone three time each. Prior to characterization and catalytic testing, all samples were dried at 110\degree C and calcined at 550\degree C for 14 hours in air to ensure complete oxidation to the spinel structure, Co\textsubscript{3}O\textsubscript{4}.

2.3.2 Wet Impregnation and Incipient Wetness Synthesis

Cu-Ag/\alpha\textsubscript{-}Al\textsubscript{2}O\textsubscript{3} based ethylene epoxidation catalysts were prepared using methodology based off of that reported in the following references [65]. First, low surface area \alpha\textsubscript{-}Al\textsubscript{2}O\textsubscript{3} was added to a solution of AgNO\textsubscript{3} dissolved in water at a volume in slight excess of that required for incipient wetness. The volume of water required for incipient wetness depends on the pore volume of the support and was measured experimentally by titrating the bare \alpha\textsubscript{-}Al\textsubscript{2}O\textsubscript{3} support with water until the incipient wetness point was reached. Weight loading was adjusted to 15\% Ag/\alpha\textsubscript{-}Al\textsubscript{2}O\textsubscript{3} by tuning the amount of AgNO\textsubscript{3} used in this step. Subsequently, the catalyst was dried in
air at room temperature to ensure the complete evaporation of water and calcined in air at 450°C for 12h to facilitate the thermal decomposition of the nitrate precursor. Water soluble salts of Cu, Re, Sn, Au, and Cs were also added at levels between 25 ppm and 1% by weight as part of a separate study focused on resolving their promotional effect on ethylene oxide selectivity. Promoters were either co-impregnated on the support with Ag or sequentially impregnated onto the Ag containing support after the Ag/α-Al₂O₃ had been dried, calcined and also reduced in a 20% hydrogen/helium stream at 300°C for 12h. X-Ag is used in catalyst nomenclature to denote a sequential impregnation preparation while (X-Ag) denotes co-impregnation, an example being (Cu-Sn)-Ag which means that Ag was impregnated, dried, and calcined before co-impregnating Cu and Sn in one step followed by an additional drying, calcination and final reduction before catalyst testing.

2.3.3 Hydrothermal Synthesis

Hydrothermal synthesis is a widely employed method involving the preparation of various materials such as metal oxides and zeolites [27, 106, 143] in a sealed vessel at elevated temperature and pressure [144]. In the work presented in this thesis, hydrothermal synthesis was used as a means of preparing MoVNb mixed oxides doped with Pd,Ni,Ti,K,Cs, and Te to be used in the partial oxidation of ethane.

Typically, synthesis proceeded by first forming a mixture of 4.03g ammonium molybdate tetrahydrate (Sigma-Aldrich, 81-83% MoO₃ basis) and 0.88g ammonium niobate (V) oxalate hydrate (Sigma-Aldrich, 99.95%) in 60ml of distilled water and heating to 50°C to ensure complete dissolution. Separately, 1.73g of vandium oxide sulfate (Sigma-Aldrich, 97%) was dissolvable in 15ml of DIW and also heated to 50°C. Additional dopants were added to the Mo+Nb mixture prior to mixing with vanadium via stock solutions of ammonium tetrachloropalladate (Sigma-Aldrich, 97%), titanium sulfate solution (Sigma-Aldrich, 99.9%), nickel sulfate (Sigma-Aldrich, 99.99%), ce-
sium sulfate (Sigma-Aldrich, 99.99%), telluric acid (Sigma-Aldrich, 98%), and/or potassium sulfate (Sigma-Aldrich, 99%); all of which were prepared separately by dissolving the precursor salts in DI water. After the addition of the dopant stock solutions to the Mo+Nb solution, the V solution was added and all components were stirred magnetically for 20 minutes. Subsequently, the mixture was transferred to Teflon vessels and sealed in autoclaves before being heated at 175°C in an oven for 48 hours. Following hydrothermal synthesis, catalysts were washed with water and acetone to precipitate and recover the mixed oxide product, which was then dried at 120°C for 2 hours and calcined at 400°C for 4 hours (10°C/min ramp) in air.

2.4 Characterization of Catalysts

2.4.1 Electron Microscopy

Transmission Electron Microscopy (TEM) is a powerful and prevalent imaging techniques which can achieve magnifications from 5,000-1,000,000x with wide applicability in the imaging of nanoparticles, biological materials, polymers and others. Typically, this involves focusing an electron beam with electromagnetic lenses on a very thin specimen leading to an image based on where the electron beam interacted with the sample. Electrons are commonly emitted thermionically from a lanthanum hexaboride filament and driven with an accelerating voltage of 50-500 kV. Interaction with the sample, or lack thereof, leads to the transmission of some electrons and the scattering of others by the electron clouds around atoms in the sample. As such, materials with greater electron densities such as metals will scatter electrons more than those with lower electron densities such as biological materials. Subsequently, the image is viewed by focusing the transmitted electrons on a fluorescent screen and the image is captured using a charge coupled device (CCD) camera [145].

In this work, TEM was used routinely to capture images of the nanoscale features present on various supported and unsupported metal and metal oxides nanoparticles.
Typically, this was accomplished by dropcasting a nanoparticle solution onto a copper TEM grid with a carbon support film and allowing the grid to fully dry prior to TEM imaging. A Hitachi H-8000 TEM operated at 200 kV was used to take standard micrographs and an aberration corrected JEM2100F-200kV FEG-STEM/TEM was used to achieve atomic resolution images of selected samples. Image analysis was carried out to quantify the size and shape distribution of the nanoparticles in the case of routine analysis and the lattice d-spacing in the case of aberration corrected atomic resolution images.

2.4.2 Scanning Electron Microscopy / Energy Dispersive X-ray Spectroscopy (SEM/EDS)

Scanning electron microscopy (SEM) is a lower magnification form of electron microscopy that involves scanning a sample with a focused beam of electrons to provide images where the surface morphology is visible. The backscatter of electrons in SEM are also useful in determining the composition of a sample through a process which is referred to as Energy Dispersive x-ray Spectroscopy (EDS). A thorough review of background and theory relevant to this technique is described in the following reference [146]. In this work, SEM was used to image supported nanoparticles and mixed metal oxides for which the features of interest were larger than 50 nm. Samples were prepared by depositing a light coating of a powder sample onto a sticky carbon sample holder.

In addition, EDS characterization was used to measure the elemental composition of catalysts for two projects discussed in this thesis, specifically, MoVNb based ethane partial oxidation catalysts and promoted Cu-Ag/α-Al2O3 ethylene epoxidation catalysts. In both cases, SEM/EDS analysis was performed using a Zeiss Ultraplus Thermal Emission Scanning Electron Microscope operated at 15 kEV and atomic percentage data was collected over three unique regions of representative morphol-
ogy such that the measurement error on top of the atomic composition could be determined.

In the case of measurements made for MoVNb based ethane partial oxidation catalysts, SEM/EDS was employed with the objectives of both confirming elemental uptakes of components into the mixed metal oxide as well as identifying unintended variations in loadings and was performed for the entire data set of 81 samples. The atomic composition of each component was then scaled to Mo=8 to omit from the measurement the presence of oxygen and carbon, which necessarily defined the error in Mo loading to equal zero. In the case of Cu-Ag/\(\alpha\)-Al\(_2\)O\(_3\) ethylene epoxidation catalysts, SEM/EDS analysis was performed on an as-needed basis to further investigate interesting morphologies which arose in certain samples.

2.4.3 X-Ray Diffraction

X-Ray Diffraction (XRD) is a widely employed characterization technique useful in determining the crystalline phases and crystallite sizes present in a material. The single requirement which makes a material suited for XRD analysis is that its atoms are arranged periodically in space in a particular arrangement known as the crystal lattice. The crystal lattice planes are spaced in a manner which is unique to a particular material and family of crystal lattices (i.e. cubic, hexagonal), making XRD very well suited for phase identification problems [147].

Constructive interference of the monochromatic X-rays of wavelength \(\lambda\) occurs when the x-rays are diffracted from successive planes in the crystalline material as a multiple of \(n\) wavelengths. The relationship between the angle and wavelength of the incident x-ray and the planes of the crystalline material are described in Bragg’s law as shown in Equation 2.16. XRD peaks are formed at different angles when Bragg’s law is satisfied by families of planes in a crystal with a particular d-spacing [147].
\[ n\lambda = 2d(sin\theta) \]  

(2.16)

Analysis of XRD patterns for all samples was carried out to verify the existence of a crystalline phase by referencing powder diffraction file databases and identify the crystal structure and grain size of each phase present in each sample. Grain size can be readily calculated using Scherrer's equation, as shown in Equation 2.17, where \( t \) is the average size of a coherently diffracting crystalline domain, \( K \) is a shape factor which is estimated to be 0.9, \( \lambda \) is the wavelength of the X-ray source, \( \theta \) is the Bragg angle, and \( \beta \) is the broadening of the peak at the full-width-half-max (FWHM) intensity [148, 149].

\[ t = \frac{K\lambda}{\beta cos\theta} \]  

(2.17)

In cases where the relative intensity of XRD peaks could be used to indicate preferential growth or crystal faceting, this variable was tracked as well. In other cases, where more than one phase was present, an analysis of the volume fraction of each phase was carried out by utilizing the relationship of direct proportionality between XRD intensity and phase concentration [150].

X-Ray Diffraction studies in this thesis were carried out using a Rigaku Miniflex II equipped with a Cu-K\( \alpha \) X-ray source and a high-speed silicon strip detector. Scans were typically carried out between 10 and 90°2\( \theta \) angle at a rate of 0.5 to 2°/min with step size of 0.02°.

2.4.4 X-Ray Photoelectron Spectroscopy

The development of X-ray Photoelectron Spectroscopy (XPS) in the 1960s earned Kai Siegbahn a Nobel Prize in Physics. XPS is a method which involves irradiating a material under vacuum with X-rays and making determinations regarding its surface structure based on the energy of its characteristic emission of photoelectrons. XPS can
be useful in the identifying and quantifying the elemental composition and chemical state of the surface of materials, where the short mean free path of the electrons mean that photoelectrons will only be detected a few nm deep [151]. Evaluation of XPS spectra involves measurement of peak locations, areas, and intensities, as these values are exactly related to the identity, chemical state and volume fraction of a phase.

In the context of this thesis, XPS was used to resolve the chemical composition of the surface species present on selected promoted Cu-Ag/\(\alpha\)-Al\(_2\)O\(_3\) ethylene epoxidation catalysts. The work presented here was is restricted to the analysis of the Ag 3d and Cu 2p spectral regions, both of which were calibrated using the Al 2s peak which has an expected value of 118 eV [151] and fitted with a Shirley background type. The XPS spectra of select samples were measured after both reductive and oxidative pretreatments such that the exact binding energies of the oxidized and metallic species could be referenced. Core photoelectron peak fitting for the Ag 3d and Cu 2p spectra were carried out by constraining the peak positions, areas, and full-width-half-max (FWHM) of the peaks which are part of these two regions. When multiple oxidation states were present, as was the case for certain Cu containing samples, this was repeated for each possible oxidation state. Peak locations were then referenced to the Handbook of XPS [151] and compared between samples of interest to understand changes in oxidation state and electron transfer between components on the catalyst surface.

2.5 **Catalytic Activity Testing**

2.5.1 **CO Oxidation Catalytic Testing**

CO oxidation activity tests for the Co\(_3\)O\(_4\) nanoparticles were carried out using 50 mg of catalyst per channel under a 2% CO/8% O\(_2\)/N\(_2\) gas stream at a space velocity of 60,000 ml-h\(^{-1}\)-gcat\(^{-1}\) The reactor effluent composition was measured via FTIR at intervals of 25°C between 25°C and 300°C. Time on stream was 30 minutes per
temperature, with ramp up and stabilization between temperatures requiring less
than 10 minutes. Catalyst bed temperatures were measured for each channel and
used in subsequent calculations. A single channel was left empty of catalytic material
in each experiment to ensure zero conversion of the empty reactor tubes. All catalytic
activities were tested under atmospheric pressure. CO conversion was calculated using
the effluent CO and CO$_2$ concentrations as shown in Equation 2.18.

$$\text{CO conversion} = (1 - \frac{CO_{out}}{CO_{out} + CO_{2, out}}) \times 100\% \quad (2.18)$$

Kinetic evaluations of catalysts were also performed by utilizing the Arrhenius
equation in Equation 2.19 where A is a pre-exponential factor, $E_a$ is the apparent
activation energy and r is the reaction rate [152]. The nomenclature of apparent ac-
tivation energy is used to the actual activation energy from the measured activation
energy, where the effects of reaction concentration at the catalyst surface on reaction
temperature cannot be compensated for [152]. In general, measurements of apparent
activation energy were made by measuring conversion over a temperature ramp at dif-erential conversions. The Arrhenius expression in Equation 2.19 was then linearized
in a plot of the natural log of rate versus inverse temperature such that the apparent
activation energy could be estimated from the slope of the plot.

$$r = a \exp\left(\frac{-E_a}{RT}\right) \quad (2.19)$$

Reaction orders were calculated using a standard power law kinetic model as
shown in Equation 2.20. In a similar manner to the calculation of apparent activation
energy, this expression is linearized such that a plot of the natural log of the reaction
rate vs. the natural log of the partial pressure of each component can be used to
estimate the reaction order of each component from the slope.

$$r = a \exp\left(\frac{-E_a}{RT}\right)P_m^{n_1}P_{C_2H_4}^{n_2} \quad (2.20)$$
FTIR Calibrations for CO Oxidation Experiments

FTIR calibrations for CO and CO$_2$ were carried out via GRAMS software and the PLS-1 regression model. Calibration points were collected at a mesh of 0.25% between 0 and 2% CO$_2$ with balance CO (CO+CO$_2$ = 2%). Specifically, the model utilized the infrared active CO stretch around 2150 cm$^{-1}$ and CO$_2$ assymetric stretch at 2350 cm$^{-1}$ shown in Figure 2.14. R$^2$ values for all 16 channels were <0.99 demonstrating excellent goodness-of-fit. To further ensure calibration accuracy, the models were applied to validation points collected between 0.5 and 2% CO and CO$_2$, the latter of which are shown in Figure 2.15. Analysis of error showed that carbon mass balances were closed with an average error of <0.5%, further proving the adequacy of the calibrations.
2.5.2 Ethylene Epoxidation Catalytic Testing

Ethylene epoxidation activity tests for co-promoted Cu-Ag/α-Al₂O₃ catalysts were carried out using 200 mg of catalyst per channel under a 10% ethylene and 10% oxygen gas stream at a space velocity of 4,000 h⁻¹. Data was collected between 215-300°C, allowing a 30 minute stabilization period at each temperature in order to be able to compare ethylene oxide selectivity at a fixed conversion (but variable temperature) level. Conversion and selectivity data collected over the temperature ramp was also used in the determination of apparent activation energies. Additionally, the partial pressure of both O₂ and C₂H₄ was varied while the other was held constant to explore the catalyst activity under oxygen rich and ethylene rich conditions and make a calculation of reaction order with respect to each component. Ethylene conversion and ethylene oxide selectivity were calculated using the effluent ethylene, ethylene oxide, and carbon dioxide concentrations using Equations 2.21 and 2.22, respectively.
It was possible to simply omit water from the calculation of ethylene conversion since its concentration is related to that of CO$_2$ by stoichiometry. This is desirable due to the inherent difficulty of making an accurate quantitative measurement of water using FTIR.

$$C_2H_4_{\text{conversion}} = (1 - \frac{C_2H_4_{\text{out}}}{C_2H_4_{\text{out}} + ETO_{\text{out}} + 0.5CO_2_{\text{out}}}) \times 100\% \quad (2.21)$$

$$ETO_{\text{selectivity}} = \frac{ETO_{\text{out}}}{ETO_{\text{out}} + 0.5CO_2_{\text{out}}} \times 100\% \quad (2.22)$$

**FTIR Calibrations for Ethylene Epoxidation Experiments**

The limit of detection for ethylene in the previously described parallel FTIR spectroscopic imaging apparatus was found to be between 0.05 and 0.125%. This means that, for a feed gas containing 10% ethylene by volume, conversions up to 99% can theoretically be measured in the experimental setup. In order to accomplish this, multivariate calibration techniques were used to quantify effluent ethylene (0-10%), EO (0-1%), and CO$_2$ (0-10%), where multivariate calibrations were necessary to quantify ethylene and ethylene oxide due to their overlapping IR bands. Accuracy of all calibration files were established by collecting validation data sets including varying levels of ethylene, ethylene oxide, and carbon dioxide and comparing expected to predicted concentrations for each species.

Generating high quality quantitative FTIR data for ethylene epoxidation requires careful calibrations accounting for the overlapping IR bands of water, ethylene oxide, C$_2$H$_4$, and CO$_2$ as shown via the representative IR spectrum of the gas phase effluent during the ethylene epoxidation reaction in Figure 2.16. This figure gives light to the overlapping IR regions of ethylene and ethylene oxide in the C-H stretching region (2700-3200 cm$^{-1}$) as well as water and ethylene in the 1200-1600 cm$^{-1}$ range and water and CO$_2$ in the 3300-4000 cm$^{-1}$ range. Due to the possibility of the CO$_2$
Figure 2.16: Sample FTIR spectrum during ethylene epoxidation reaction for different catalysts

stretching peak at 2350 cm\(^{-1}\) becoming saturated at concentrations greater than 2% both the stretch and the CO\(_2\) overtone peak required calibration.

FTIR calibrations for ethylene epoxidation were carried out via GRAMS software and the PLS-1 regression model. To ensure calibration accuracy, the models were applied to validation points collected between 0-0.5% ethylene oxide and 0-6% C\(_2\)H\(_4\). The expected and predicted points are shown in Figure 2.17.

The average relative error of each channel is shown in Figure 2.18 showing that all errors are under 10% and are actually slightly higher for C\(_2\)H\(_4\) predictions than ethylene oxide.

Validation points for the CO\(_2\) stretch and overtone calibrations were collected between 0-2% and 2-10%, respectively. The actual vs. predicted concentrations for
these validations are shown in Figure 2.19.

2.5.3 Ethane Partial Oxidation Catalytic Testing

Ethane partial oxidation tests were performed using an ethane to oxygen ratio of 4:5 (40% ethane, 50% oxygen, 10% nitrogen). On stream results were analyzed with a Shimadzu Gas Chromatograph GC2014 equipped with a TCD detector to analyze the product distribution. The experiments were carried out in a quartz tube plug flow reactor operating at ambient pressure, where the space velocity was kept at a constant 1200 hr⁻¹. The catalysts were used as synthesized and a temperature ramp ranging from 120-460°C was used with 30°C step sizes to probe the temperature profile of each catalyst. Temperature measurements were taken inside the catalyst bed using an insulated K-type thermocouple. Ethane conversion and selectivity toward acetic acid,
Figure 2.18: Relative error for $C_2H_4$ and EO calibration predictions

Figure 2.19: Validation of CO$_2$ HTR FTIR calibrations for asymmetric stretching and overtone regions
ethylene, carbon monoxide, and carbon dioxide were calculated using Equations 2.23, 2.24, 2.25, 2.26, and 2.27, respectively.

\[
C_2H_6\text{conversion} = (1 - \frac{C_2H_6,\text{out}}{C_2H_6,\text{in}}) \times 100\% \quad (2.23)
\]

\[
AA\text{selectivity} = \frac{AA_{\text{out}}}{C_2H_4,\text{out} + 0.5CO_{\text{out}} + 0.5CO_2,\text{out} + AA_{\text{out}}} \quad (2.24)
\]

\[
C_2H_4\text{selectivity} = \frac{C_2H_4,\text{out}}{C_2H_4,\text{out} + 0.5CO_{\text{out}} + 0.5CO_2,\text{out} + AA_{\text{out}}} \quad (2.25)
\]

\[
CO\text{selectivity} = \frac{0.5CO_{\text{out}}}{C_2H_4,\text{out} + 0.5CO_{\text{out}} + 0.5CO_2,\text{out} + AA_{\text{out}}} \quad (2.26)
\]

\[
CO_2\text{selectivity} = \frac{0.5CO_2,\text{out}}{C_2H_4,\text{out} + 0.5CO_{\text{out}} + 0.5CO_2,\text{out} + AA_{\text{out}}} \quad (2.27)
\]

2.6 Gold Nanoparticle Synthesis

Gold nanoparticles are among the most well studied class of nanomaterials which can be prepared via conventional colloidal synthesis techniques [153, 154]. This fact is largely owed to their stability and utility in numerous applications including but not limited to catalysis and biotechnology (ie. drug delivery) [77, 155–157]. Most modern AuNP synthesis techniques techniques are related in one way or another to methodology pioneered by Turkevich/Frens methods [158, 159] and Brust/Schiffrin [160]. The Turkevich method, introduced in the 1950s, involves reacting hot chloroauric acid with sodium citrate at low concentrations in an aqueous medium and generally produces relatively monodisperse quasi-spherical particles in the 10-20nm diameter range. [158] The ingenuity of this method was in its simplicity; as at the prescribed temperatures, trisodium citrate is able to act as both a reducing agent to form Au\textsubscript{0} ions subject to nucleation and growth, as well as a capping agent to bind to the Au
surface atoms to stabilize surface energy and prevent rampant Ostwald ripening. In the 1970s, G. Frens made the logical jump that control over the particle size distribution of the colloid could be afforded through tailoring the ratio between citrate and chloroauric acid in solution [159].

Another famous technique in the family of gold nanoparticle synthesis is that developed by Brust and Schiffrin in the early 1990s which enabled the fabrication of smaller, monodisperse particles by utilizing organic solvents such as toluene, a sodium borohydride reducing agent and most importantly, tetraoctylammonium bromide (TOAB); a quaternary ammonium compound capable of acting as both a protective agent and a phase transfer agent [160]. Since its introduction, this methodology is often augmented to include the use of alkanethiol protective agent which is more successful than TOAB in preventing long term aggregation of particles in solution.

A drawback of the original Turkevich/Frens methodology is that the low reduction potential of citrate limits the minimum sizes which can be accessed and the loss of colloid stabilization at decreased citrate concentrations limits the practical maximum size. Many researchers have found ways to circumvent these problems and increase the viability of the core methodology to fabricate a wider range of monodisperse nanoparticle sizes. [161] [162] [163] [164] [165] For example, Sivaraman et al found that reversing the order of reactant addition and adding chloroauric acid to hot citrate led to the formation of stable monodisperse colloids <10 nm by creating conditions which were simultaneously more favorable nucleation and more effective for stabilization. This is postulated to be an effect of the pH where the nucleation and stabilization were enhanced through initially being at acidic and neutral conditions, respectively. [164] Other interesting modifications include co-employing citrate with other stronger reducing agents such as ascorbic acid and sodium borohydride and utilizing seeded growth methods where stable monodisperse colloids of progressively greater sizes are
fabricated by using intermediate sized particles as nucleation seeds. [156, 166]

Several strategies were employed in this work to leverage the knowledge base in the literature to establish a high level of control over the size of aqueous gold nanoparticle dispersions, the ultimate goal being the ability to prepare monodisperse solutions of AuNPs with on-demand size control. This included validation experiments of varied synthesis methodologies reported in the literature, literature-based factorial screening designs to target size control via reagent concentrations, and one factor at a time (OFAT) experiments varying reagent concentrations of interest.

2.6.1 Validation of Existing Gold Nanoparticle Synthesis Methodology

In order to leverage the existing knowledge base of gold synthesis methodology existing in the literature and establish a starting point for continued experiments several well-known synthesis procedures were reproduced for validation purposes. These included the original Brust method [160] reported to produce AuNPs in the 1-3 nm range, where 30 mmol/dm$^{-3}$ of HAuCl$_4$ in 30 ml of water and 50 mmol/dm$^{-3}$ of tetraoctylammonium brodie (TOAB), a quaternary ammonium complex, in 80 ml of toluene were combined to form a two-phase mixture. Upon stirring, the TOAB acts as a phase transfer agent to move the gold salt from the aqueous to the organic phase where the subsequent addition of 170 mg of dodecanethiol was added to protect the gold and 0.4 mol/dm$^{-3}$ of NaBH$_4$ was, slowly, added to reduce the gold salt. After 3 hours the synthesis was complete and the organic portion of the mixture was washed with acetone and centrifuged thrice.

Another experimental method validated was the room temperature synthesis of 5 nm AuNPs using sodium citrate and NaBH$_4$ reported by Liang et al [156]. In this method, 2.54 ml of 0.01M HAuCl$_4$ was added to 88.46 ml of DIW followed by the addition of 2 ml of 38.8 mM sodium citrate solution. After the two had mixed, a 1 ml mixture of freshly prepared 0.075 wt% NaBH$_4$ solution in 38.8 mM citrate was
added to the gold salt and citrate mixture while stirring to reduce the gold salt and form AuNPs reported by the authors to have an average diameter of 5 nm.

Also reported in the same work by Liang et al [156] was the thermal citrate method. This method involved heating 1 ml of 1% HAuCl₄ to a boil in 100 ml of DI water before quickly adding 5 ml of 1% sodium citrate to reduce the gold salt while boiling for 20 minutes. In this case, the authors reported AuNP diameters in the 18-20 nm range. They also reported the preparation of 10 nm average diameter AuNPs with the so-called reverse citrate method. This method involves heating 6 ml of 1% sodium citrate solution in 100 ml of water to boiling before adding 1 ml of a 1% HAuCl₄ solution and boiling for an additional 15 minutes to reduce the gold salt and form AuNPs reported by the authors to have diameters in the 10-12 nm range.

The final set of experimental methods validated were part of a seeded method reported by Jana et al [166] where AuNP samples with diameters ranging from 5-40 nm were prepared using a 3.5± 0.7 nm Au seed. This technique is touted as a way to grow large gold nanoparticles with more uniform sizes and shapes than would be realizable with a non-seeded method. The seed was synthesized with the room temperature NaBH₄ assisted reduction of HAuCl₄ with sodium citrate protection. Specifically, 20 ml of 2.5x10⁻⁴ M HAuCl₄ and 2.5x10⁻⁴ M trisodium citrate were mixed before adding 0.6 ml of cold 0.1M NaBH₄. This seed solution was then used together with a growth solution to prepare larger diameter AuNP solutions. The growth solution consisted of 200 ml of 2.5x10⁻⁴ M HAuCl₄ combined with 6 g of cetyltrimethylammonium bromide (CTAB) at a concentration of 0.08M. This mixture needed to be heated to dissolve the CTAB and re-cooled prior to use. The first AuNP sample, referred to as Seeding A, had a reported average diameter of 5.5±0.6 nm. Seeding A was synthesized by mixing 7.5 ml of growth solution with 0.05 ml of fresh 0.1M ascorbic acid solution before adding 2.5 ml of seed solution and stirring for 10 minutes. The next sample, referred to as Seeding B, had a reported diameter of
8.0±0.8 nm and was synthesized by mixing 9 ml of growth solution with 0.05 ml of 0.1M ascorbic acid solution before adding 1 ml of seed solution and stirring for 10 minutes. Finally, a sample referred to as Seeding C with a reported diameter of 17±2.5 nm and a rod+sphere mix of morphologies was prepared by mixing 9 ml of growth solution with 0.05 ml of 0.1M ascorbic acid solution before adding 1 ml of Seeding B solution and stirring for 10 minutes.

### 2.6.2 Modification of Existing Gold Nanoparticle Synthesis Methodology

#### Thermal Citrate Method

As previously described, the thermal citrate method is an excellent candidate in the fabrication of gold nanoparticle dispersions between 10 and 20 nm. In this work, a modified thermal citrate method was utilized based loosely off that reported by Liang et al [156]. Specifically, 0.001M HAuCl₄ was first heated to 100°C in de-ionized water (DIW), after which 5 ml of DIW containing trisodium citrate was added at the following citrate:gold molar ratios: 10, 7.5, 5, 2.5, 1. The combined gold+citrate solution was then held at 100°C for 15 minutes, during which nucleation and nanoparticle growth commenced.

#### Reverse Citrate Method

When the colloid is heated to 100°C, trisodium citrate can act as a reducing agent in addition to a capping agent and theoretically should lead to the fabrication of smaller gold nanoparticles sizes at equivalent citrate:gold molar ratios used in the thermal citrate method. The reverse citrate method was modified by heating up solutions of trisodium citrate dihydride in DIW at varied concentrations to 100°C and subsequently adding room temperature solutions of HAuCl₄ in 5 ml DIW, allowing the solution to stir at 100°C for 15 minutes. The concentration of gold in solution was fixed at 0.001M and the citrate concentration was varied at the following citrate:gold
molar ratios: 15, 10, 7.5, 5, 2.5.

**Room-Temperature NaBH$_4$ Assisted Method**

At room temperature the role of citrate in the AuNP synthesis is to act as a protective agent toward Oswald Ripening of the Au particles, controlling the ultimate size and dispersion of the colloid. As it was desired to change the room temperature NaBH$_4$ assisted AuNP synthesis method to produce larger AuNPs, modifications were made by changing both the HAuCl$_4$ concentration from 0.1-0.2 M and the C/G molar ratio from 1.5-4.5 independently.

**2.7 RAFT Polymerization**

Reversible Addition-Fragmentation Chain Transfer (RAFT) is a living free radical polymerization technique invented in 1998 by the Commonwealth Scientific and Industrial Research Organization (CSIRO) which is suited for the polymerization of a large family of functional monomers through its degenerative chain transfer process [167]. RAFT is frequently employed in areas such as drug delivery, tissue engineering, and membrane science among others [168–170]. Limitations of RAFT chemistry include the lack of one or two universal chain transfer agents suited to all chemistries as well as difficulties encountered when extending this technique to efficiently fabricate block co-polymers when monomers differ in their reactivities [167].

RAFT chemistry establishes a kinetic control regime over the degree of polymerization which is unique from radical-radical terminations which are central to other radical polymerization methods. Specifically, this is accomplished through reversibly trapping the radical as chain growth commences. Dithioester chain transfer agents (also known as RAFT agents) capable of forming carbon centered radicals which can undergo $\beta$-scission or form leaving groups facilitate this chemistry. RAFT provides the ability to fabricate novel architectures and useful end-group functionalities
through manipulation of the Z- and R-group chemistry of the chain transfer agent, which is not possible when using other well established polymerization techniques such as atom transfer radical polymerization (ATRP). An important factor in RAFT polymerization is the choice of a RAFT agent where the R group chemistry is amenable to both β-scission and polymerization initiation, such that equilibrium is maintained between chain growth and the formation of dormant poly-RAFT agent where there is more dormant than active species [167].

In this work, the RAFT polymerization of tert-butyl acrylate (tBA) procedure reported by Liang et al [156] was adapted to fabricate ptBA with lengths ranging from 11 to 397 repeat units. This was accomplished mainly through controlling the amount of monomer used in the RAFT polymerization process, as will be discussed in detail later.

2.7.1 Synthesis of the RAFT Agent

Methyl-2-(butylthiocarbonothioylthio) propanoate, the RAFT agent employed in this work, was synthesized based on the procedure described in the enclosed reference [156]. The exact procedure was carried out as follows. A mixture of 10 ml of 1-butanethiol, 14.3 ml of triethylamine (TEA) and 100 ml of dichloromethane (DCM) was stirred under Ar before adding a mixture of 6.18 ml of carbon disulfide (CS₂) and 50 ml of DCM over a 30 minute period using a syringe pump. After the addition the mixture was stirred for 1 hour prior to adding a mixture of 6.18 ml of carbon disulfide (CS₂) and 50 ml of DCM over a 30 minute period using a syringe pump. After stirring for 2 hours the excess solvent was evaporated and the remaining solid was dissolved in diethyl ether, causing the precipitation of a TEA-HBr salt which was subsequently filtered using filter paper and by pulling a light water-induced vacuum. The methyl-2-(butylthiocarbonothioylthio) propanoate in ether was then washed thrice with both 50 ml of ice cold 10% HCl solution and 50 ml of DIW prior to drying overnight in a
vessel enclosed with anhydrous MgSO$_4$. The ether was evaporated and the product was purified by performing column chromatography with an in-house constructed 19:1 pentane/ethyl acetate column. Specifically, a packed slurry was made by adding quartz wool and 3 cm of SiO$_2$ to the bottom of a column followed by filling the column half full with solvent. Subsequently, SiO$_2$ was added to the solvent to create the slurry and the RAFT agent was dissolved in 5 ml of the 19:1 pentane/ethyl acetate mixture and added dropwise to the column. The second band was isolated.

2.7.2 RAFT Polymerization of tert-Butyl Acrylate

A typical polymerization was carried out as follows, using the procedure adapted from Liang et al [156]. 226.8 mg (0.90 mmol) of methyl-2-(butylthiocarbonothioylthio) propanoate, the RAFT agent, was added with 14.8 mg (0.90 mmol) of AIBN, the initiator, and 5.2 ml (36 mmol) tBA liquid monomer to a round bottom flask and purged for 30 minutes while stirring with Argon. A schematic of the apparatus used, in lieu of the Schlenk tubes typically employed for air sensitive chemistry, is shown in Figure 2.20. Prior to use, 4-Methoxyphenol (MEHQ) inhibitor was removed from the tBA monomer by passing the tBA over a basic alumina column and discarding the first 5 ml. Additionally, the AIBN was purified by recrystallization in methanol. Polymerization was then initiated by heating the solution in an oil bath to 55°C and holding for 1.5 hours, or until the stir bar stopped. The polymerization was subsequently quenched with liquid nitrogen before dissolution of the ptBA in the smallest possible volume of THF. The ptBA was then precipitated from the THF with 200-500 ml of ice cold 1/1 by volume methanol/water mixture, the exact amount depending on how much was needed for sufficient precipitation. The methanol/water mixture was then carefully decanted and the isolated polymer was dried under vacuum at room temperature overnight. The quoted procedure yielded polymers with 35.8 repeat units. Polymer lengths were tuned from 11 to 397 repeat units by adjusting
the ratio of tBA monomer to RAFT agent.

2.7.3 Acid Hydrolysis of poly-tert-Butyl Acrylate

The ptBA prepared via RAFT polymerization was converted into polyacrylic acid (PAA) via acid hydrolysis prior to AuNP functionalization using methodology adapted from Wu et al [171]. Specifically, 2.5 g of ptBA was dissolved in 20 mL of 1,4-dioxane with 3 ml of 37% fuming HCl solution and heated while stirring under reflux at a temperature of 101°C. The solution was refluxed until a visible layer of tert-butyl alcohol formed in the flask (typically 5+ hours), at which point the reflux condenser was removed and the tert-butyl alcohol was removed by evaporation while stirring at 190°C. The PAA was then precipitated from the 1,4-dioxane through the addition of ether which was then decanted from the precipitate. Finally, the PAA was dried under vacuum at room temperature overnight.
2.7.4 Preparation of Functionalized PAA-AuNPs

The functionalization of prepared aqueous solutions of AuNPs with PAA was carried out using a procedure adapted from Liang et al [156]. In a typical functionalization, 15 mg of PAA in a 3 ml aqueous solution containing 0.1M NaHCO₃ was added to a 100 ml aqueous solution containing approximately 5 mg of AuNPs and stirred overnight. Following functionalization, the citrate and excess PAA were removed from solution through precipitation with ultracentrifugation at 100,000 g for 1 hour and washing with DIW (3 times).

2.8 Characterization of Functionalized PAA-AuNPs

Due to the large number of unique PAA-AuNP samples prepared, which varied in their AuNP diameters and PAA chain lengths, and the large experimental expense of doing exhaustive characterization on every sample, full characterization was performed only on a single PAA-AuNP sample which consisted of 5.98 AuNPs and PAA with 35.8 repeat units. This being said, polymer length, nanoparticle size, and nanoparticle concentration was determined for each unique sample using GPC, TEM and UV-Vis. Additional tests confirming polymer chemistry (1H-NMR, FTIR) before and after conversion from ptBA to PAA, hydrodynamic radius before and after grafting PAA to the AuNP surface (DLS), AuNP crystalline structure (XRD, HRTEM), and the grafting density of PAA on the AuNPs (TGA) were carried out for the representative sample only (5.98 nm AuNPs, 35.8 repeat unit PAA).

2.8.1 Transmission Electron Microscopy (TEM)

Routine images were taken of all as-synthesized gold nanoparticle samples using a Hitachi H-8000 Transmission Electron Microscope (TEM) at magnifications between 20-200 kX and an accelerating voltage of 200 kV. Selected samples were also imaged using an aberration corrected JEM2100F-200kV FEG-STEM/TEM to achieve atomic
resolution images revealing crystalline phase and surface faceting of the AuNPs. The
time, operating principles and data analysis relevant to the TEM analysis of AuNPs
is similar to that presented in regard to catalyst characterization in a previous section.

2.8.2 Nuclear magnetic resonance spectroscopy (NMR)

Nuclear magnetic resonance spectroscopy (NMR) is a prevalent technique useful in
structurally resolving molecules based on their characteristic energy absorption when
exposed to electromagnetic radiation under a strong magnetic field. In this process,
absorbance of electromagnetic energy of particular frequencies happens through mag-
netic resonance involving the compounds nuclei, of which the most commonly studied
are \(^{1}\)H or \(^{13}\)C. The resultant NMR spectrum is a collection of the frequency and in-
tensities of the energy absorption under the magnetic field and it’s features may be
qualified and quantified to gain insights into the chemical structure of the molecule
in question.[172–174] Applications of NMR are vast and range from the structural
elucidation of organics such as proteins and polymers [156, 171, 175] to applications
in nanoparticle synthesis and solid state chemistry [176, 177].

Several features are of importance when considering the \(^{1}\)H-NMR spectrum of a
molecule which are highly relevant to the analysis of data in this thesis. Specifically,
each unique peak or set of peaks in the spectrum corresponds to a set a protons
within the molecule that have equivalent magnetic environments as a result of being
shielded to equivalent degrees by the electrons in their environment. This causes
the set of protons in question to have equal chemical shifts in NMR and appear
in the same position on the x-axis. Additionally, peaks in NMR have varied areas
and multiplicities, where multiplicity refers to the number of peaks in a set. The
integrated area of the peak is directly proportional to the number of protons which
are contributing to that peak while the multiplicity of the peak is a result of number
of neighboring protons (ie. protons on atoms adjacent to the nucleus producing the
signal). Chemical shift, which is usually referred to as $\delta$ and measured in parts per million (ppm) is a measure of the frequency of the NMR signal coming from a nucleus, where a lower value of $\delta$ indicates that resonance of that nucleus required a stronger magnetic field.

The exact chemical shift of a set of protons in a molecule measured with $^1$H-NMR will be determined by the precise magnetic environment created by said molecule. As such, a strategy for the interpretation of $^1$H-NMR spectra usually involves combining the general rules of thumb of approximating proton chemical shifts with the possible integrated areas and multiplicities based on the expected chemistry. For example, one could envision a scenario where it is necessary to differentiate between two singlets which, from integration, appear to belong to CH$_3$ groups. In this case, their unique chemical shifts would be a result of how shielded they are by electrons on other nearby atoms. For example, a proton on an allylic group will be more shielded than one on a ketone and be chemically shifted upfield as a result. [172–174]

In this work, $^1$H-NMR measurements were made using a Bruker Avance III-HD 300 MHz instrument. Deuterated solvents were selected as to not interfere with the $^1$H-NMR signal of the molecules of interest (CDCl$_3$ in the case of the methyl-2-(butylthiocarbonothioylthio) propanoate RAFT agent and ptBA, MeOD in the case of PAA) as well as providing known reference peaks on the NMR spectra for calibration of chemical shift. Data acquisition was controlled with IconNMR software and the time domain results (e.g., FID) were processed using SpinWorks [178] through several steps. First, the time domain data was fourier transformed to produce frequency domain data. At this point, the frequency domain data must be phased to correct for instrumental anomalies which occurred during FID acquisition and effect the quality and appearance of the frequency domain peaks through the imperfect separation of absorptive and dispersive modes. The process of phasing is essentially mathematically tuning how the two are combined to produce a spectrum which ap-
pears entirely absorptive. This topic is covered in detail in the enclosed references [179, 180]. Subsequently, the spectrum was shifted based on the expected peak of the deuterated solvent and the chemical shifts, integrated intensities and multiplicities of each signal were collected for interpretation.

2.8.3 Gel Permeation Chromatography (GPC)

Gel Permeation Chromatography (GPC) is a size exclusion chromatography (SEC) technique which, since its conception by Lathe and Ruthven in 1955, has gained a great deal of popularity in the analysis and purification of polymers [156, 181]. Like all chromatography techniques, GPC involves passing an analyte in a mobile phase through a stationary phase which interacts with the analyte. In the case of GPC, smaller polymers or proteins interact less with the stationary phase and elute faster while larger polymers and proteins elute more slowly [181]. In this work, GPC measurements were made using a Waters 2414 Column and Refractive Index Detector. Molecular weight determinations were based on the retention time of the analyte compared to regularly updated calibrations performed with polystyrene latex standards of known molecular weight. The information gleaned from GPC analysis is typically the weight average molecular weight (Mw), which refers to the average molecular weight where there are equal masses of polymers on either side, and the polydispersity ratio (PDI) which is defined as the ratio between the weight average molecular weight (Mw) and the number average molecular weight (Mn). The number average molecular weight is defined as the molecular weight in a distribution of polymers where there are equal numbers of polymers on either side. PDI is a simple indicator of the range of molecular weights which populate a sample.
2.8.4 Thermogravimetric Analysis (TGA)

Thermogravimetric analysis (TGA) is a technique involving the controlled heating and precision weighing of a sample under a controlled atmosphere. Ultimately, this technique provides information on the change of mass of a sample as a function of temperature [182]. Modern TGA systems provide the ability to control atmosphere and heating regimen and are often paired with additional instruments such as FTIR [183] or mass spectrometers which allow the cocurrent analysis of decomposition products or differential mechanical analysis (DMA) which is used to measure make stress vs. strain measurements. These features make TGA useful in a number of studies regarding the thermal stability, decomposition and kinetics of inorganic and organic materials such as heterogeneous catalysts and polymers [156, 184].

Within fields like catalysis, TGA is useful in the determination of quantities such as the amount of coke deposited on a catalyst surface during a reaction [185] and the amount of surfactants such as PVP leftover on the surface of nanoparticles [176]. Other applications include the use of TGA to quantify the weight percent of various components in a material based on their unique thermal decomposition temperatures and studies of phase transition behaviors. [186] TGA also has a great deal of utility in the analysis of functionalized nanoparticles by facilitating the determination of the amount of grafted organic material or tests of thermal stability [156, 168, 187, 188].

TGA involves considering either a weight or rate of weight loss versus temperature plot [182]. Several features in the weight vs. temperature curve are of interest in the analysis of TGA data including regions where the weight plateaus with respect to temperature, regions with maximum slopes which represent rapid weight loss, and regions with minimum slopes which can be used to identify the formation of compounds. In routine TGA analysis, the plot of mass vs. temperature is often smoothed or manipulated by taking the derivative to make the inflection points in
In this work, a TGA-50 Shimadzu Thermogravimetric Analyzer equipped with a TGA-50H detector was used to make a measurement of the grafting density of thiolated PAA attached to Au NPs. Using the information obtained from the AuNP TEM studies and GPC polymer length analysis, it’s possible to calculate the mass of PAA on the particle and the grafting density in terms of PAA chains/particle and PAA chains/nm$^2$. First, the surface area (SA) and volume (V) of an AuNP can be found using the particle diameter ($D_{TEM}$) measured with TEM. Using these values together with the density of Au metal ($\rho_{Au}$) is 19.32 g/cm$^3$, which is based on the molar mass of the metal and the fcc unit cell packing density the Au particle mass ($m_{Au}$) can be calculated. Subsequently, the mass of the Au particle can be used to estimate the mass of PAA on the particle based on the composition measured with TGA. Finally, the mass of PAA on the particle and the PAA molecular weight determined with GPC can be used to determine the number of PAA chains per particle or per unit surface area.

2.8.5 UV-Vis Spectroscopy

Solutions of gold nanoparticles exhibit surface-plasmon resonant properties [153, 189]. Surface plasmon resonance, which results from conduction band electron oscillation in the presence of electromagnetic radiation, creates in a sharp absorbance peak in the visible region as indicated on Figure 2.21. Since UV-Vis is a technique which measures absorbance, Beer’s Law is applicable at low concentrations where the absorbance is between 0.1 and 1. Higher concentrations, typically exceeding 0.1 mmol/L may lead to deviations due to molecular interactions and non-linearities in the UV-Vis detection system. Beer’s Law states that Absorbance (A) is equal to the product of the molar absorptivity ($\epsilon$), the path length of the cell (L) and the concentration of the solution (C) as shown in Equation 2.28 [190].
Beer’s Law and UV-Vis are extremely useful in the prediction of the size and concentration of AuNP samples, but require the prior knowledge of the molar absorptivity ($\epsilon$). Thus, in using UV-Vis measurements to predict unknowns about a AuNP sample one must already have experimentally measured the molar absorptivity of that sample or will need to rely on size based predictions reported by others. In this work, this was accomplished by measuring the absorbance of the as synthesized nanoparticles of known concentrations at different dilutions to build a relationship between nanoparticle concentration and absorbance, as has been shown in Figure 2.21. From this data, the molar absorptivity was calculated and used in subsequent determinations of nanoparticle concentration which needed to be made after the functionalization and centrifugation steps. This methodology is described in detail in the work by Liu et al, where a correlation curve between AuNP size and extinction coefficient which can be used in lieu of a lab measurement is also provided [191].

2.8.6 Dynamic Light Scattering (DLS)

Dynamic Light Scattering (DLS) is a highly useful methodology in determining the size of particles in a colloidal solution. Specifically, DLS measures the change in wavelength of light, referred to as a Doppler shift, which occurs as a result of the light being scattered by spherical particles in Brownian motion. By examining how light from a laser is modulated by the colloidal solution, information can be inferred regarding the size distribution of spherical particles and their diffusivity in solution [192].

In this work, DLS was used to provide a measurement of hydrodynamic radii of the gold nanoparticles before and after surface functionalization with PAA. Specifically, this was accomplished by preparing solutions of AuNP of varying concentrations and
Figure 2.21: UV-Vis spectra of aqueous solutions of citrate capped 5.98 nm AuNPs at varied concentration measuring the autocorrelation function using a Malvern Zetasizer ZS90 instrument. By surveying a range of concentrations, it was possible to establish a reliable DLS measurement on a non-light absorbing colloid. To ensure an accurate measurement, the range of dilutions for which the calculated average radius remained semi-constant was taken as the true average hydrodynamic radius of the colloid.
CHAPTER 3
COBALT OXIDE CATALYZED CO OXIDATION

Colloidal synthesis of nanoparticles is a versatile approach used to prepare materials with drastically different properties, potentially allowing them to be tailored for a wide range of applications in medicine, catalysis, and more [24]. However, the difficulty in understanding relationships between synthesis conditions, desirable properties, and material performance is a limiting factor in the utility of these methods. An example of one such system are cobalt oxide nanoparticles. The properties of cobalt oxide nanomaterials, such as phase, morphology and crystal faceting are known to affect properties such as active site density and redox properties which are important for catalyst reactivity in various oxidation and hydrogenation reactions, but the accessibility of these features through nanoparticle synthesis is poorly established [25–33].

The numerous shape, size, and structure sensitivities that have been reported for cobalt oxide nanocatalysts make them interesting materials to study. One such example is the ease at which Co$_3$O$_4$ can form electrophilic oxygen species (either O$^-$ or O$^{2-}$), as indicated by the concentration of these species on the oxide surface. Miyamoto et al showed using rectangular NH$_3$ pulse techniques that the surface oxygen contents were different for Co$_3$O$_4$ formed through the thermal decomposition of cobalt (II) carbonate when compared to Co$_3$O$_4$ formed through the hydrolysis of cobalt (II) nitrate [50]. This work was elaborated on by the Cao group who showed that cobalt oxides prepared using a soft reactive grinding (SRG) procedure had very high propane total oxidation rates which correlated with high concentrations of su-
perficial electrophilic oxygen (O\textsuperscript{−}) as evidenced by peak speciation in O\textsubscript{2}-TPD results [42]. The same group suggested that enhanced stability and activity among certain samples could be further linked to increased surface defects created by long periods of grinding and evidenced by lattice distortion seen in XRD. Surface defects such as vacancies or steps and bulk extended defects such as dislocations, stacking faults, and twins are a reality of transition metal oxides which can potentially change the adsorption properties (eg. surface oxygen bond strength) and reactivity of the surfaces which they inhabit [51]. Work by Sadykov et al definitively linked cobalt oxide defect density, which they defined indirectly by measuring the amount of weakly bonded oxygen, with catalytic activity for CO oxidation by demonstrating a linear dependence between the two when defect density was controlled via the preparation procedure [51].

The bulk oxygen mobility in cobalt oxide materials is another important property related to structure and catalytic reactivity [42, 52]. Potentially, for metal oxides involved in catalytic reactions with mechanisms which utilize their surface redox functionality, this variable could drastically affect reaction rates [47]. This is due to an enhanced ability of the metal oxide to resupply the surface reaction with lattice oxygen. In recent years, researchers have begun to recognize the sensitivity of this variable to factors such as grain boundary consolidation, where the coalescence of grains can increase oxygen diffusion rates from the bulk, among other favorable effects [49].

The surface enrichment of the Co\textsuperscript{3+} cation in Co\textsubscript{3}O\textsubscript{4} is perhaps the most heavily discussed cobalt oxide structure sensitivity in heterogeneous catalysis. Co\textsubscript{3}O\textsubscript{4} has a regular spinel structure which contains a mix of octahedrally coordinated Co\textsuperscript{3+} cations and tetrahedrally coordinated Co\textsuperscript{2+} cations. The relative amounts of these cation types on the surface of Co\textsubscript{3}O\textsubscript{4} nanoparticles can be tuned via the surface faceting of the nanoparticles and/or the degree of spinel inversion. Control over the
Co$_3$O$_4$ cation distribution has been the subject of a great deal of research, as Co$^{3+}$ surface enrichment and control over the Co$^{3+}$/Co$^{2+}$ ratio have been established to dramatically affect specific reaction rates, stabilities, and light-off temperatures for many catalytic applications [53–56].

These structure sensitives are, in one form or another, a consequence of the preparation conditions and variables used in the preparation of the cobalt oxide catalyst. However, most works dedicated toward the understanding of these relationships are extremely restricted in scope and don’t consider the co-dependence of various synthesis variables and structural descriptors. Thus, only with careful experimental design where numerous variables of interest are simultaneously tracked is it possible to link preparation conditions, catalyst structure, and performance. To this end, factors known to be linked to cobalt oxide size and structure within the colloidal synthesis family were screened to establish their importance on structural properties and build predictive models with which to tune these properties [58, 59]. A series of 2-level factorial designs and response surface designs were used throughout the project with the aim of discerning the roles of factors involved in the synthesis of cobalt oxide nanoparticles through the thermal decomposition of cobalt acetate with diols in dibenzyl ether and discovering their influence on nanoparticle properties (size, morphology, phase) and catalyst performance in CO oxidation.

3.1 Factorial Screening Design

Design of experiments was first paired with high throughput activity tests to study the influence of six synthesis conditions on the CO oxidation activity of unsupported cobalt oxide nanoparticles. In all, the performance of 29 unique cobalt oxide catalysts were evaluated in less than two days. Paired with the relative efficiency of a six factor designed experiment over its one factor at a time analog, total experimental time was decreased by a factor of 50.
Table 3.1: Initial factorial screening design for the synthesis of CoOx nanocatalysts

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low Level (-)</th>
<th>High Level (+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Aging temperature (°C)</td>
<td>240</td>
<td>270</td>
</tr>
<tr>
<td>B: Heating rate (°C/min)</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>C: Surfactant (M)</td>
<td>0.05</td>
<td>0.25</td>
</tr>
<tr>
<td>D: Cobalt acetate (M)</td>
<td>0.05</td>
<td>0.15</td>
</tr>
<tr>
<td>E: Reductant (M)/Cobalt(M)</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>F: Surfactant Type</td>
<td>OA</td>
<td>PVP</td>
</tr>
</tbody>
</table>

The cobalt catalyst library was prepared via thermal reduction of cobalt acetate with 1,2-dodecanediol, a procedure which is elaborated on in the experimental section. Synthesis parameters reported in literature to influence the size, morphology, and crystal structure of cobalt nanoparticles prepared with this method were varied at levels representative of the entire design space [58, 59]. Specifically, the synthesis was carried out using 0.05-0.15 M cobalt acetate and 0.05-0.25M of either polyvinyl pyrrolidone (PVP) or oleic acid surfactants in 30 ml of dibenzyl ether, at a temperature of 240-270°C, a ramp rate of 1-10°C/min, using reducer-reductant molar ratios from 2-8. The levels of the factorial screening design are shown in Table 3.1.

Factorial design of experiments was employed to systematically study these factors and x-ray diffraction studies were carried out to resolve the influence of the factors on the bulk crystal structure of the particles. Crystalline phase was determined for each sample based on the relationship between lattice parameters, miller indices, and d-spacing for cobalt, and Scherrer’s equation was applied to approximate crystallite size from peak broadening [148, 193]. Prior to catalytic testing, all samples were dried at 110°C and calcined at 550°C for 14 h in air to ensure complete oxidation to the spinel structure, Co₃O₄. The post calcination cobalt oxide grain sizes ranged from 32-100 nm, as shown in Table 3.2.

CO oxidation activity tests for the Co₃O₄ nanoparticles were carried out using 50 mg of catalyst per channel under a 2% CO/8% O₂/N₂ gas stream at a space
velocity of 60,000 ml-h$^{-1}$-gcat$^{-1}$ The reactor effluent composition was measured via FTIR at intervals of 25°C between 25°C and 300°C. Time on stream was 30 minutes per temperature, with ramp up and stabilization between temperatures requiring less than 10 minutes. Catalyst bed temperatures were measured for each channel and used in subsequent calculations. A single channel was left empty of catalytic material in each experiment to ensure zero conversion of the empty reactor tubes. All catalytic activities were tested under atmospheric pressure. The synthesis conditions of each catalyst tested is listed in Table 3.2 where Surf stands for Surfactant, Red/Co stands for Reducer/Cobalt molar ratio, XS stands for grain size and, and r stands for CO oxidation activity at 200°C.

3.1.1 CoO$_x$ screening design: statistical analysis of synthesis factors on catalyst structure

The results shown in Table 3.2, which populated multiple one-half fractional factorial designs over the six factors were analyzed using Minitab statistical software. A pareto analysis showing the relevant model terms for three responses of interest is shown in Figure 3.1 where the x-axis is the standardized effect of each model term which is equivalent to the coefficient of that term in the regression model scaled by the standard error of said coefficient. Larger standardized effects are indicative of model terms which are statistically more important. It should be noted that certain terms are retained in the regression models in order to maintain model hierarchy (ie. inclusion of term ABC requires the inclusion of terms A, B, C, AB, AC, and BC regardless of their p-values). These terms are omitted from Figure 3.1 and only the statistically significant model terms (ie. p-values less than 0.05) are shown.

The responses outlined in Figure 3.1 include nanoparticle formation, which was treated as a binary response characterized by presence or absence of crystalline XRD peaks. Specifically, a value of 0 would be entered for an X-ray amorphous sample and
Table 3.2: Synthesis conditions and, XRD grain sizes, CO oxidation light off temperatures and activities at 200 °C of factorial screening design cobalt oxide samples

<table>
<thead>
<tr>
<th>#</th>
<th>Temp °C</th>
<th>Ramp °C/min</th>
<th>Surf M</th>
<th>CoAc M</th>
<th>Red/Co</th>
<th>Surf</th>
<th>XS nm</th>
<th>T50 °C</th>
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<td>1</td>
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<td>0.05</td>
<td>2</td>
<td>PVP</td>
<td>64.7</td>
<td>119</td>
<td>0.58</td>
</tr>
<tr>
<td>24</td>
<td>270</td>
<td>1</td>
<td>0.05</td>
<td>0.15</td>
<td>8</td>
<td>PVP</td>
<td>58</td>
<td>162</td>
<td>0.43</td>
</tr>
<tr>
<td>25</td>
<td>240</td>
<td>10</td>
<td>0.05</td>
<td>0.15</td>
<td>2</td>
<td>OA</td>
<td>47</td>
<td>172</td>
<td>1.72</td>
</tr>
<tr>
<td>26</td>
<td>270</td>
<td>10</td>
<td>0.05</td>
<td>0.05</td>
<td>8</td>
<td>OA</td>
<td>54</td>
<td>160</td>
<td>0.53</td>
</tr>
<tr>
<td>27</td>
<td>270</td>
<td>1</td>
<td>0.25</td>
<td>0.15</td>
<td>2</td>
<td>OA</td>
<td></td>
<td>302</td>
<td>1.09</td>
</tr>
<tr>
<td>28</td>
<td>240</td>
<td>10</td>
<td>0.25</td>
<td>0.15</td>
<td>8</td>
<td>PVP</td>
<td>60</td>
<td>146</td>
<td>1.69</td>
</tr>
<tr>
<td>29</td>
<td>255</td>
<td>5.5</td>
<td>0.15</td>
<td>0.1</td>
<td>5</td>
<td>OA</td>
<td>76</td>
<td>192</td>
<td>0.55</td>
</tr>
</tbody>
</table>
a value of 1 would be entered for a sample with visible X-ray diffraction. It should be noted that this semi-arbitrary cut off value could possibly erroneously omit CoOx samples with very small crystallite sizes which appear X-ray amorphous. This assay facilitated a quick determination of nanoparticle synthesis success and avoided the high cost of carrying out electron microscopy analysis on 60+ samples which would be out of the scope of a screening experiment. The synthesis temperature (factor A) was an important factor in the success or failure of the nanoparticle synthesis, where low temperatures were associated on average, with less nanoparticle formation. The term CE was also found to be important, which can be physically interpreted as the need for more moles of capping agent when higher concentrations of reducing agent per mole of cobalt were used. This could be an artifact of the assay used, as one would expect very small and possibly x-ray amorphous particles to form under these conditions.

The pareto analysis of the CoOx grain size, measured by applying Scherrer’s equation to the FWHM of the XRD peaks, was also analyzed and is shown in Figure 3.1. It was found that an increased level of CoAc concentration (factor D) was the single most important variable in controlling grain size, where higher concentrations led to larger grains. Of secondary importance was the concentration of the surfactant (factor C), where increasing C would decrease the particle grain size. XRD was also used to quantify the percentage of fcc vs hcp CoO crystalline phases from the XRD data, which is shown as a third response in Figure 3.1. This response was considerably more complex than others studied with respect to the synthesis factors. Specifically, it was found that increasing the CoAc concentration (factor D) favored the rock salt (fcc) structure, but that when the heating ramp (factor B) or the surfactant concentration (factor C) was also increased that the hcp (wurtzite CoO) structure was favored. The pareto analysis of crystal phase also featured a fourth order interaction, namely BCDE, of which a physical interpretation is nearly impossible and is only
A notable result from the statistical analysis of the synthesis factors listed in Table 3.1 was the absence of factor F, the surfactant type, from the fitted models and Pareto analysis shown in Figure 3.1. This finding can be better understood by considering the chemistry of each capping agent. Oleic acid (OA) is a long chain fatty acid with the formula C$_{18}$H$_{34}$O$_2$ and is commonly employed as a capping agent for hydrophobic nanoparticles. It forms a strongly interacting layer around the particles which acts as a barrier to mass transfer and limits magnetic and van der Waals interactions [59, 183, 194]. In comparable solution phase synthesis reports of cobalt based nanoparticles, adding 0.25M OA was found to decrease the average particle size from 18 nm to 6 nm [183]. In the same study, FTIR experiments led to the conclusion that stabilization was achieved via bridging bidentate interactions between OA and Co metal atoms. Polyvinylpyrrolidone (PVP) is a high molecular weight (Mn of approximately 40,000 Da) non-ionic polymer with C=O, C-N, and CH$_2$ functionality. Since PVP has mixed functionality, having both a highly polar, hydrophilic amine group on the pyrrolidone ring and a hydrophobic alkyl group, it is a suitable protective agent.
Figure 3.2: TEM images of f-CoO nanoparticles synthesized with 0.10M Co(Ac), a
250°C aging temperature, a 10°C/min heating rate, a polyol:Co ratio of 5 and a) OA
and b) PVP protection

for many different nanoparticle and solvent systems [176].

Statistically, there was no effect of using PVP versus OA as a protective agent in
terms of particle size, grain size, crystalline phase, or catalytic activity of the prepared
materials. This is highlighted for a single case in Figures 3.2 and 3.3 where the TEM
micrographs and resultant size distributions are compared for f-CoO nanoparticles
synthesized with 0.10M Co(Ac), a 250°C aging temperature, a 10°C/min heating
rate, a polyol:Co ratio of 5 and a) 0.25M OA or b) 0.25M PVP. This suggests that
the mechanism of protection for both PVP and OA originates from the hydrophobic
carbon chains interacting with one another to create steric hindrances.

3.1.2 CoOx Screening Design: Statistical Analysis of Synthesis Factors on
Catalyst Activity

In a typical experiment measuring catalytic activity, several FTIR scans were taken
at each temperature point and averaged to improve the SNR of the rapid-scanning
spectrometer. Subsequently, univariate calibrations were applied to quantify both
CO and CO₂ outlet concentrations based on the absorbance of the CO and CO₂
vibrational bands. In all cases, the carbon balance over the conditions studied was closed with a variation of ±1.5%. From this information, catalytic activities (ml/g-s) were calculated in the range of 0.09-1.72 ml/g-s, taking into account the precise catalyst mass, flow rate, and CO converted in each channel. Light off temperatures (T50) at 50% CO conversion ranged from 119-302°C.

The results were used to develop a predictive model correlating the aforementioned cobalt synthesis parameters with CO oxidation activity at 200°C. Factorial analysis and model regression was performed using Minitab statistical software. Specifically, twenty-three of the Co3O4 catalysts tested with the HT system were used to fit the statistical model while the remaining six were used for validation. Only terms with a p-value < 0.05 were included in the model. It has been found that cobalt concentration, surfactant concentration, and surfactant type are the most significant main effects. Further analysis of the significant two-way interaction effect for ramp rate and temperature showed that increasing ramp rate positively influences activity at low
Figure 3.4: CO oxidation activity at 200°C (ml/g-s) - contour from statistical model synthesis temperatures, but has an opposite influence at high synthesis temperatures. This interaction is shown in the contour map in Figure 3.4.

The statistical model presented is accurate and can self-predict very well. The predictive ability of the model is shown in Figure 3.5, where both model development points and model validation points are included. Model reproducibility was evaluated by carrying out repeat synthesis and catalytic testing on several design points. Between replicates, differences ranged from 0.41%-6.39% and did not change the predictive model appreciably. This demonstrates the usefulness of the high throughput system in resolving the changes in catalytic performance produced by the breadth of synthesis conditions studied.

In summary, the factorial analysis of CO oxidation on cobalt oxides proved useful in probing the synthesis parameter design space and directing future studies. An accurate and reproducible model correlating Co$_3$O$_4$ synthesis parameters with CO
oxidation activity was quickly formulated by pairing DOE with the high throughput reactor and rapid-scan FTIR system. Here, with evidence of significant curvature, a response surface study is necessary to fully understand underlying complexities. While several regions of interests have been identified for further investigation, the most promising are the high/low combinations of the synthesis temperature/ramp rate interaction.

3.2 Central Comsite Design

Two factors, previously investigated in the factorial screening design shown in Table 3.1 were selected for continued experimentation using a more detailed response surface design, the levels of which are shown in Table 3.3. The two factors, CoAc concentration and synthesis temperature were correlated with a number of interesting
structural changes in the CoOx materials, such as nanoparticle formation, grain size, and crystal phase as well as being linked to the CO oxidation activity.

While the empirical models generated with factorial designs cannot be relied upon to make high accuracy predictions outside in regions of extrapolation they do provide excellent information regarding trends within the design space and can be used to inform the experimenter of the desired design space region in which to carry out more detailed experimental efforts such as those integral to response surface designs. As such, the CO oxidation activity at 200°C predicted by the factorial design previously described was used to extrapolate the activity with respect to the two factors of greatest interest, CoAC concentration and synthesis temperature as shown in Figure 3.6. The dotted gray box is representative of the interpolated activity predicted by the model (i.e. within factor parameter bounds). The curvature of the extrapolated region was used to recast the levels of the model parameters for continued investigation. The selected levels are indicated with the dotted red box, which when investigated with a RSD will include multiple center point replicates, factorial points (shown as the red rectangle on the RHS of Figure 3.6) and axial points (shown as the red circle on the RHS of Figure 3.6).

3.3 Control of Structure and Morphology

X-ray diffraction and TEM studies were carried out to resolve the influence of the synthesis factors on the bulk crystal structure, morphology, grain size and particle size of the catalysts. Crystalline phase was determined for each sample based on the relationship between lattice parameters, miller indices, and d-spacing for cobalt, and
Scherrer’s equation was applied to approximate crystallite size from peak broadening [148, 193]. Size distribution and morphology was studied using transmission electron microscopy (TEM) as well as HRTEM for selected samples. It was found that CoO particles in the 1-100 nm size range were synthesized with both cubic and hexagonal close packed crystal structure (herein referred to as f-CoO and h-CoO, respectively). Additional phases observed in the full factorial design were alkoxide type and layered-hydroxy structure type precursors.

Figure 3.7 contains TEM micrographs of selected samples synthesized according to the levels selected for the CCD (Table 3.3) and illustrates the variability in the size and morphology of particles obtained as a function of just cobalt acetate concentration and aging temperature. A clear correlation where increasing cobalt acetate concentration increases particle size and polydispersity is visually evident, but a more refined understanding of how metal concentration and aging temperature affect particle sizes and dispersions requires statistical analysis. By carrying out a least-squares regression and pareto analysis of our design variables and corresponding terms, we
can learn how much the population mean of particle size and dispersion changes with respect to each term when scaled by standard error. In doing this, we can see which terms have the greatest effect on the particle size and dispersion when error is accounted for and be confident that these terms are important when control over particle size and dispersion are desired. This analysis confirms that cobalt acetate concentration is the most important factor studied in the control of particle size and dispersion. However, it also suggests that the effect of increasing cobalt acetate concentration is sensitive to the aging temperature employed. At aging temperatures below 250°C, increasing cobalt acetate concentration has the effect of changing the crystal structure from f-CoO to h-CoO and layered cobalt hydroxy and alkoxy acetates whilst at 250°C and above, increasing cobalt acetate concentration increases size and polydispersity of the particles while maintaining a f-CoO phase.

XRD analysis aided in elucidation of the phases formed and the grain sizes existing within the particles. Interestingly, the CoOx grain sizes measured were not found to change in the same ways as the particle sizes measured with TEM. In the case of grain size, aging temperature, cobalt acetate concentration and surfactant concentration were found to be important, and the largest grain sizes were formed at low concentrations of cobalt acetate and low aging temperatures or high concentrations of cobalt acetate and high aging temperatures. Thus, CoO particles with increasingly small grain sizes were obtained at intermediate aging temperatures and cobalt salt concentrations. Incidentally, the same region of the design space led to the fabrication of large particles up to 80 nm in size. From this information, together with visual inspection of TEM images such as those in Figure 3.7, it is clear that a certain balance of cobalt salt concentration and aging temperature, as well as sensitivity to other variables studied in the screening design (Table 3.1) can lead to grain boundary consolidation for f-CoO structures. Consolidation was not observed for the h-CoO or LHS structures synthesized at lower temperatures. An example of this type
of morphology is shown in Figure 3.8, where small particles are coalesced into stable aggregates. Intuitively, we might expect this to happen when the f-CoO growth rate exceeds the nucleation rate. The highest degrees of grain boundary consolidation were found to exist close to the center point of the central composite design (Table 3.3) at 0.06M cobalt acetate and a 250°C aging temperature. Moving away from this region in any direction was found to decrease the level of grain consolidation.

Numerous schemes have been proposed to quantify the grain boundary coalescence in nanomaterials which use a combination of experimentally measured values of BET surface area and the diameter of grains and/or particle aggregates measured
with TEM and XRD [49]. Henceforth, the scheme proposed by Tsybulya et al [195] will be used when discussing grain boundary consolidation, where the degree of coalescence is defined as the ratio between the particle size, including particle aggregates, measured with Transmission Electron Microscopy (TEM) and the grain size measured by applying Scherrer’s equation to the X-Ray Diffraction (XRD) pattern [148, 149]. This relationship is shown in Equation 3.1

$$\eta = \frac{D_{TEM}}{D_{XRD}}$$ \hspace{1cm} (3.1)

Based on the phases fabricated in the totality of experiments (including both screening design and CCD), relationships between synthesis factors and crystalline phase can be elucidated. Specifically, for the factorial screening design (Table 3.1), aging temperatures were between 240°C and 270°C, all samples were comprised of
either h-CoO, f-CoO, or a mix of the two. In this region of the design space, it was found that the %h-CoO in the sample was increased by increasing the aging temperature from 240 to 270°C, provided that surfactant concentration and cobalt salt concentrations were low (on the order of 0.05M). Additionally, it was found that increasing the concentration of 1,2-dodecanediol in the synthesis decreased the %h-CoO. The finding that high temperature could induce a kinetically controlled regime leading to h-CoO crystals which would be diminished by increasing the level of surfactant in the synthesis, effectively slowing the thermal decomposition rate, is comparable to the results of others. For example, Nam et al found that the thermal decomposition of cobalt acetylacetonate at rapid ramp rates and high temperatures led to h-CoO while low ramp rates, low temperatures, and long aging times led to c-CoO [196]. Additionally, they found that the addition of dichlorobenzene to the reaction mixture had the effect of first increasing the aspect ratio of h-CoO to yield rods and finally yielding c-CoO at higher concentrations. In contrast, no dependence was found in this work on heating rate or aging time.

Samples synthesized at CCD levels (Table 3.3), over a 179-321°C temperature range, led to four distinct outcomes in terms of crystalline phase. Intermediate cobalt acetate concentration and low temperature (179°C and 0.06M) yielded a mixture of large cubes and rods with edge lengths and diameters of 93.6±10.6 nm which was indexed to match a layered cobalt hydroxy structure (Co(OH)(CH₃COO), PDF#22-0582) [197]. Similar morphologies were prepared by Poul et al in their studies of layered hydroxide metal acetates which they describe as being structurally similar to hydrozincite structures layered with unidentate coordinated acetate ions [198]. This type of structure is comparable with our material as evidenced by XRD and ex-situ FTIR spectral analysis shown with black in Figures 3.9a and 3.9b, respectively, which confirms the existence of blue shifted acetate νas (C=O) and νs (C=O) bands indicative of acetates with unidentate coordination to Co²⁺ [199]. At low aging temperature
and cobalt acetate concentration (200°C and 0.02M) spherical particles with a TEM measured diameter of 10.3±2.6 nm were synthesized. Repeat syntheses under these conditions led to materials that were either x-ray amorphous or structurally similar to cobalt alkoxide and alkoxyacetate phases seen by others characterized by the intense low angle diffraction peaks of layered structures [198, 199]. The XRD reflections of this phase are shown in red in Figure 3.9a. In this type of lamellar structure, cobalt-oxygen units are separated by alcohalate anions originating from the polyol solvent or reducing agent as well as the acetate anion, in some cases. At the 200°C and 0.02M CoAc synthesis condition, splitting of the νs (CH) and νas (CH) bands originating from the diolate anion in ex-situ FTIR, shown in red in Figure 3.9b, suggests that the Co2+ is chelated by the diol as well as being coordinated in a unidentate manner to the acetate anion [199]. At low temperature and higher cobalt acetate concentration (200°C and 0.1M), particles of 57.2±20.2 nm were formed with mixed h/f-CoO structures (PDF#s 89-2803 and 78-0431). At temperatures of 240°C and above over the entire range of cobalt acetate concentrations investigated only f-CoO crystals were obtained with particle sizes ranging from 22.2 nm to 82.7 nm.

The fabrication of metastable phases is consistent with a solution phase reduction of cobalt salt which exists in a kinetic rather than thermodynamically controlled regime [200, 201]. Additionally, aging temperatures at 200°C or below are likely not high enough to induce thermal decomposition of the CoO precursor meaning that the final product obtained, a layered hydroxy acetate may be considered an intermediate in the formation of CoO. For these reasons, it is not completely surprising that cobalt based nanostructures of a number of different phases were obtained over the entirety of the designs; including h-CoO, f-CoO, h/f-CoO mixtures, cobalt hydroxy acetate and cobalt alkoxy acetate based structures.

Interestingly, the collection of h-CoO and h-CoO/f-CoO structures originating from both the screening and central composite design were found to differ in their
Figure 3.9: a) XRD and b) ex-situ FTIR of Co alkoxy and hydroxy acetate structures formed at synthesis temperatures <250°C

crystal faceting evidenced by XRD. The ratio between h-CoO (002) and (100) XRD reflections varies between samples, which is suggestive of preferential growth along the c-axis of the wurtzite structure [202, 203]. An example of h-CoO nanoparticles with varying degrees of faceting are shown in Figure 3.10 where the bottom (pink) XRD pattern is representative of no faceting and the top (black) pattern represents the highest observed degree of faceting. All samples shown in Figure 3.10 were prepared at aging temperatures between 200-270°C, where the degree of faceting is primarily changing as a function of the heating rate (1-10°C/min) and cobalt acetate concentration (0.05-0.15M). Since f-CoO was often in coexistence with h-CoO, the volume of each phase was accounted for when considering the effect of this variable on activity. Interestingly, the f-CoO/h-CoO ratio alone was not found to have a correlative
relationship with CO oxidation activity. This is likely because changes in this variable were convoluted with changes in f-CoO grain boundary consolidation and h-CoO faceting, both of which more strongly influenced the catalytic properties.

The degree of h-CoO faceting (measured via the (002)/(100) XRD intensity ratio) was found, from statistical analysis, to be very sensitive to aging temperature, heating rate and cobalt salt concentration. Specifically, considering an aging temperature of 280°C, increased growth along the c-axis could be achieved by decreasing the heating rate whilst at high (>0.1M) cobalt acetate levels or increasing the cobalt acetate concentration whilst at using low (<5°C/min) heating rates. Additionally, increasing the aging temperature when low heating rates (1°C/min) were employed decreased growth in the c-direction while increasing aging temperature when high heating rates (10°C/min) were employed increased the degree of faceting. In order to maximize the anisotropic growth in h-CoO crystals, a combination of low aging temperature (<250°C) and low heating rates (<6°C/min) were most effective in forming h-CoO in favor of c-CoO, and under these conditions, increasing the cobalt acetate concentration led to more faceted particles. While c-axis growth is an intrinsic property of wurtzite crystal systems it is diminished when the process is not kinetically driven. Thus, establishing faster growth kinetics through temperature, heating regimen, and increased metal salt concentration has generally been found to produce high surface area, more anisotropic wurtzite crystals [196, 204, 205].

To understand the formation of h-CoO it is necessary to consider how this phase is related to other phases fabricated. Some work has suggested that f-CoO could be an intermediate in the oxidation of h-CoO to Co₃O₄ [196], which would help explain the common co-existence of these phases in this work. Another possibility is that these phases arise from distinct synthesis intermediates arising when cobalt acetate partially or fully decomposes in solution and complexes with the diol reducing agent, producing the same or similar intermediate coordinated CoO structures such as those
Figure 3.10: XRD patterns of h-CoO nanoparticles prepared at varied synthesis conditions showing preferential growth along the c-axis (black: 200°C, 5.5°C/min, 0.1M CoAc, blue: 270°C, 1°C/min, 0.15M CoAc, green: 270°C, 10°C/min, 0.05M CoAc, orange: 270°C, 10°C/min, 0.15M CoAc, pink: 270°C, 1°C/min, 0.05M CoAc) which form at low temperatures as previously discussed. Time resolved synthesis experiments were carried out to address these possibilities focused on the center point of the CCD (0.06M CoAc, 250°C) which had the terminal phase of f-CoO. Aliquots were sampled from the reflux vessel during the heat-up phase at 100°C, 200°C, and every 30 minutes once the reaction reached the 250°C aging temperature. The XRD patterns of these aliquots are shown in Figure 3.11. Prior to reaching 250°C a unique diffraction pattern was observed with low index peaks between 20-30°2θ comparable to, but not identical to, the layered alkoxy-acetate structures previously discussed. Once aging at 250°C commenced, f-CoO was formed immediately, and no further
Figure 3.11: Time-resolved synthesis of f-CoO nanoparticles with 0.06M CoAc at 250°C

phase change was observed for the duration of refluxing which totaled 180 minutes, providing no evidence that f-CoO formation proceeds through a h-CoO intermediate. Additionally, analysis of the XRD peak broadening with Scherrer’s equation and TEM image analysis showed that grain size and particle size remained virtually unchanged for the duration of the 180 minute thermal aging.

3.4 CO Oxidation Activity

The highest CO oxidation activities, coinciding with the lowest light off temperatures were achieved with catalysts synthesized at higher cobalt acetate concentrations and intermediate synthesis temperatures. This conclusion is supported by the statistical analysis of the activity data via the factorial screening and response surface designs (Tables 3.1 and 3.3) which show that cobalt acetate concentration and its interaction with synthesis temperature were the most important variables. Additionally, by measuring apparent activation energies using the high-throughput reactor (Table 3.4), it was observed that the activation barrier for CO oxidation was also changing as a function of synthesis conditions. The simultaneous change of activity and apparent activation energy indicates that the increased activity is not simply due to a higher
Table 3.4: Synthesis conditions and structural properties of selected RSD catalysts

<table>
<thead>
<tr>
<th>Synthesis</th>
<th>Phase (pre-calcination)</th>
<th>$\eta$</th>
<th>$\text{T50} (^\circ \text{C})$</th>
<th>$\text{Ea} (\text{kJ/mol})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1M CoAc, 200°C</td>
<td>h-CoO</td>
<td>1</td>
<td>84.3±1.6</td>
<td>30.2±5.0</td>
</tr>
<tr>
<td>0.06M CoAc, 250°C</td>
<td>c-CoO</td>
<td>6</td>
<td>105.2±1.5</td>
<td>50.8±4.4</td>
</tr>
<tr>
<td>0.1M CoAc, 300°C</td>
<td>c-CoO</td>
<td>1</td>
<td>162.3±3.0</td>
<td>67.4±5.8</td>
</tr>
</tbody>
</table>

Figure 3.12: CO oxidation light-off curves for selected RSD catalysts

fraction of exposed catalytically active centers, but that the active center is different. Figure 3.12 shows three selected catalysts with varied light off temperatures and activation energies. More specifically, one without any grain boundary consolidation or h-CoO faceting, one with an intermediate degree of grain boundary consolidation ($\eta=6$) and one with the highest measured degree of h-CoO faceting measured with XRD.
3.5 Synthesis-Structure-Activity Relationships

The model generated via the central composite design around cobalt acetate concentration and aging temperature shows that the CO oxidation light-off temperature appears to be decreased by increasing the cobalt acetate concentration and decreasing the aging temperature during the synthesis, as depicted in Figure 3.13. Comparison of the dependence of light-off temperature on synthesis variables to the dependence of structural properties points to possible explanations for observed variations in catalytic activity. An interesting example is the variation of grain boundary consolidation ($\eta$) on synthesis variables, as depicted in Figure 3.14. As previously stated, $\eta$ is maximized at the center point of the CCD (0.06M CoAc, 250°C), and follows similar curvature to that of the light-off temperature contour in Figure 3.13. One notable difference is that the optima in the two contour plots do not exactly coincide. This can be explained by the optimum light-off temperature being associated with a faceted h-CoO intermediate having been formed at 0.1M and 200°C. In fact, cross-checking this result with the formation of other faceted h-CoO nanoparticles in the screening design confirms that these types of structures tend to be formed at low ramp rates, low aging temperatures and high CoAc concentrations. This is depicted in Figure 3.15, where optimum growth along the h-CoO c-axis coincides with low ramp rates and high cobalt acetate concentration.

To further investigate these correlations, the CO oxidation light-off temperature was plotted against $\eta$ for all samples which exhibited this characteristic. It should be noted that this relationship was identified during the analysis of the response surface design, but to further validate the relationship, catalysts from the entirety of the experimental design sets were sampled. As shown in Figure 3.16, as $\eta$ increases, CO oxidation light off temperature decreases, although diminishing effects are observed at $\eta>8$. It should be noted that in this analysis $\eta$ is changing mainly as a function of grain size and particle size and that other structural variables, such as the
Figure 3.13: Light-off temperature contour map developed with CCD

Figure 3.14: Grain boundary consolidation contour map developed with CCD
pre-calcination phase, are constant. Moreover, neither particle size or grain size independently showed a significant correlation with catalytic activity in contrast to other reports which have suggested that smaller particles favor activity due to their greater number of low coordination atoms [30, 206]. Here, by directly comparing those two effects it’s evident that the consolidation of grain boundaries is significantly more important than the particle size alone.

High activities in oxidation reactions have been previously correlated with metal oxide grain boundaries with the primary reason being fast oxygen diffusion from bulk to surface to participate in the surface reaction with close proximity active sites. This hypothesis has been corroborated in detail in studies dealing with CuOx catalyzed CO oxidation, LaCo$_{1-x}$Fe$_x$O$_3$ catalyzed CH$_4$ oxidation, and oxygen diffusion rates along grain boundaries [47, 51, 207, 208].

A similar assessment can be made regarding the coincidence of high CO oxidation activity with the formation of faceted CoO hcp particles by considering all relevant
samples. In fact, plotting this variable with respect to the CO oxidation rate at 150°C confirms the relationship between higher h-CoO XRD intensity ratios and CO oxidation activity, as shown in Figure 3.17. Since the CoO catalysts are calcined before being tested for CO oxidation, it is of interest to understand how a highly faceted h-CoO nanoparticle evolves into a more active Co$_3$O$_4$ catalyst than its h-CoO counterpart with a low degree of faceting. Intuitively, one might reason that higher CO oxidation rates arising from faceted h-CoO structures must be related to a greater number of active sites being preferentially exposed on the Co$_3$O$_4$ structure after calcination, especially when the expectation is that the morphology of the CoO intermediate would be preserved [196]. Indeed, HRTEM micrographs of the highly faceted h-CoO after calcination to Co$_3$O$_4$ reveal surface termination by (110) facets rather than the (111) and (001) facets typical of Co$_3$O$_4$ nanoparticles. This is evidenced in Figure 3.18a
which shows a faceted Co$_3$O$_4$ sample originating from faceted h-CoO with 0.286 nm d-spacing belonging to the \{220\} family while Figure 3.18b shows a Co$_3$O$_4$ sample of semi-spherical morphology originating from non-faceted f-CoO exhibiting \{111\} facets [53, 56]. High activity originating from Co$_3$O$_4$ [110] facets has been attributed to its enrichment with octahedrally coordinated Co$^{3+}$ cations which have been shown to exhibit favorable CO adsorption properties and lower barriers for reaction between adsorbed CO and oxygen [26, 53]. To our knowledge, the finding that faceted h-CoO can be oxidized in air at high temperature to form faceted Co$_3$O$_4$ exposing the Co$^{3+}$ enriched [110] surface is novel and presents a unique methodology for control over cobalt oxide surface structure.

Figure 3.17: Relationship between CO oxidation activity and h-CoO faceting
Figure 3.18: HRTEM images of Co$_3$O$_4$ originating from a) faceted h-CoO and b) f-CoO

3.6 Conclusions

Iterative statistical design of experiments and high-throughput screening were used to study the effect of synthesis parameters in the one-pot colloidal synthesis of CoOx on nanoparticle properties and catalytic activity in CO oxidation. Of the six variables studied, it was found that the concentration of CoAc used in the synthesis together with the synthesis aging temperature had the most significant impact on nanoparticle structure and catalyst activity with light off temperatures below 90°C occurring above 0.06M CoAc and below 250°C. It was found that variations in light off temperatures with the CoAc concentration and aging temperature could largely be explained with the structure of the catalyst pre-calcination. In part, activity variations coincided with f-CoO particles with high degrees of grain boundary consolidation, $\eta$, formed at intermediate aging temperatures and CoAc concentrations which could enhance activity by providing active sites in close proximity to grain boundaries with fast oxygen diffusion from the bulk. Activity variations also coincided with the formation of h-CoO particles which exhibited preferential growth along the c-axis. The latter
tended to form at low ramp rates, low aging temperatures, and high CoAc concentrations and were shown with HRTEM studies to oxidize into \( \text{Co}_3\text{O}_4 \) with highly active (110) surface facets and \( \text{Co}^{3+} \) enrichment. These findings demonstrate that \( \text{Co}^{3+} \) and grain boundary enrichment are the most significant structural variables in a design space assessing multiple properties and provide a novel approach in the control of these properties.

Additionally, analysis of the effects of synthesis temperature and cobalt precursor concentration on the apparent activation energies and light off temperatures suggest that the response surface design successfully moved toward a region of improved catalyst performance. In fact, the lowest light off temperature measured in the screening design was 119°C, which is larger than the majority of the light off temperatures measured in the response surface design. It should be noted however, that despite leading to a region of improved catalyst performance, the curvature predicted in the extrapolated region by the screening design was erroneous as the optimum activities were expected to fall at the lowest combinations of synthesis temperature and cobalt acetate concentration. This finding highlights the limitation of factorial screening designs and the importance of carrying out a detailed response surface design to improve the prediction accuracy, especially when extrapolating to new regions in the design space.
Chapter 4

Cu-Ag Catalyzed Ethylene Epoxidation

The work exploring Cu-Ag catalyzed ethylene epoxidation described in this thesis aims to define a formal relationship between catalyst formulation, structure, feed composition, and epoxide selectivity for Cu-containing Ag/α-Al₂O₃ ethylene epoxidation catalysts. Initial experiments were carried out to investigate the effects of copper weight loading (0-50,000 ppm) on 15% w/w Ag/α-Al₂O₃ catalysts at varied operating conditions (ie. varied ethylene partial pressure, oxygen partial pressure, and temperature) using high throughput reactor studies. The main objective of the first portion of this work was understanding how the catalyst activity changes with respect to these conditions and how this is related to the phase of the Cu-Ag material, considering deactivation modes proposed at high C₂H₄ and O₂ partial pressures proposed in the literature [78, 209].

The selectivity and stability of the Cu-Ag/α-Al₂O₃ catalysts as a function of operating conditions and Cu loading studied were used to guide the next subsequent round of experimentation which was focused on incorporating co-promoters into the optimized Cu-Ag system. Co-promoters investigated were selected based on those with known activity in ethylene epoxidation or the possibility of having a stabilizing effect on the Cu-Ag system and included elements such as Cs, Sn, Pd, Re, Mo, Zn, and Au, among others. Co-promoters found to impart a desirable effect on the ethylene epoxidation activity when compared to a base 15% Ag/α-Al₂O₃ catalyst were studied using a series of 2² factorial designs focused on the catalyst impregnation order and co-promoter loading. Further tests were carried out for co-promoted catalysts which
focused on understanding the effect of Cu loading on optimized co-promoted catalysts.

4.1 Addition of Cu to base Ag/α-Al₂O₃ catalysts

Figure 4.1 shows the ethylene oxide selectivity at 5.8±0.1% ethylene conversion for 15% Ag/α-Al₂O₃ catalysts containing varying amounts of copper, where error bars represent standard errors from 2-3 repeat measurements. In order to make a comparison at a semi constant conversion level data was collected between 230-275°C in a feed of 10% ethylene and 10% oxygen. The superiority of the 0.2%Cu-15% Ag/α-Al₂O₃ ethylene oxide selectivity to other loadings is striking, particularly when compared to higher Cu loadings (1 and 5% Cu) which yield lower ethylene oxide selectivities when compared to the base silver formulation. The higher selectivity measured for 0.2%Cu-15% Ag/α-Al₂O₃ is comparable to that reported by Barteau et al where a silver catalyst with 0.2% Cu loading converted 6% ethylene and was 34% selective to ethylene oxide at 540K under the same reactant feed condition [66].

The obvious question which comes to mind when considering the results of Figure 4.1 is why the EO selectivity is only benefited by the 0.2%Cu catalyst and is worsened by increasing levels of Cu loading. There is little agreement in the field on the active phase of Cu-Ag under ethylene epoxidation reaction conditions [65, 76, 78, 210, 211] and one would expect this to be quite sensitive to how reducing or oxidizing the environment is. To elaborate, following the theoretical modeling and experimental efforts of Barteau et al which suggested increased EO selectivities could be afforded through the use of Cu and the formation of a surface Cu-Ag alloy [64–66] additional studies have suggested alternative explanations. Several studies have suggested that Cu-Ag catalysts form CuO surface layers and perhaps CuO-AgO layers under oxidizing conditions as evidenced by in situ XPS and DFT studies [88]. Other work has gone on to suggest that the thin CuO layer is responsible for the increased activity by increasing the number of metal-oxygen bonds relative to metal-carbon...
Figure 4.1: Ethylene oxide selectivity at 5.8±0.1% ethylene conversion for 15% Ag/α-Al₂O₃ catalysts containing varying amounts of Cu bonds [211] or alternatively, that the metastable oxygen involved in the Cu₂O-CuO phase transition is responsible for increased selectivities [210]. Work investigating Cu only ethylene epoxidation catalysts have suggested that the Cu will begin to oxidize at partial pressures as low as 1.2x10⁻⁴ mbar and that ultimately CuO will be formed under reaction conditions [212] while others have found that the active species can be maintained by keeping the oxygen partial pressure close to 0.07 [76].

The mixed findings regarding the active phase and promotional effect of Cu-Ag catalysts are a testament to the difficulty of making meaningful conclusions when comparing results between various experimental labs and theoretical groups whose testing procedures, catalyst synthesis methodology and assumptions are inherently different. Thus far, no single study has fully addressed this, where even the most comprehensive single piece of work which has been completed, where reaction per-
formance and kinetics were examined for a series of Cu-Ag catalysts with varied Cu loading, did not address how the Cu oxidation state and catalyst surface might be changing with respect to the independent variables [66]. As such, the need for a systemic, parallelized study which considers how the catalyst activity and surface structure changes as a function of Cu loading and feed composition is apparent. This motivated the investigation into how the activity of the 15% Ag/α-Al₂O₃ catalysts changes when the ratio between C₂H₄ and O₂ changes for different Cu loadings was carried out, the results of which are shown in Figure 4.2. The results show that as the ratio between C₂H₄ and O₂ increased, making the environment more reducing, all of the Cu-Ag catalysts increased in EO selectivity at least slightly. Of particular interest was the very sharp increase in EO observed in the case of the 1%Cu-15% Ag/α-Al₂O₃ catalyst, which almost doubled as soon as the feed gas became ethylene rich and then stabilized after further increases in C₂H₄/O₂ ratio. We might also note here that the general trend of increased EO selectivities with respect to increased ethylene partial pressure does not jive with the aforementioned theories suggesting that thin CuO surface oxides or metastable oxygen involved in the Cu₂O-CuO phase transition [210, 211] explain Cu’s promotional effect in Cu-Ag catalysts.

The basic mechanism for ethylene epoxidation is shown in Equations 4.1-4.4, where the kinetically relevant steps are steps 4.1 and 4.3 [64].

\[ O₂ + * \leftrightarrow 2O* \] (4.1)

\[ C₂H₄ + 2* \leftrightarrow C₂H₄* \] (4.2)

\[ C₂H₄* + O* \leftrightarrow CH₂CH₂O* \] (4.3)

\[ CH₂CH₂O* \leftrightarrow CH₂CH₂O + * \] (4.4)
When dissociation of oxygen is the rate determining step the reaction rate should increase with the partial pressure of oxygen and be independent of the partial pressure of ethylene, yielding a positive oxygen reaction order and an ethylene reaction order of approximately zero. If the surface reaction between ethylene and oxygen is rate limiting the reaction rate should increase with the partial pressures of both reactants, yielding positive reaction orders for both. Analysis of the reaction order data shows that oxygen dissociation, Equation 4.1 is the rate limiting step for 15% Ag/α-Al₂O₃ catalysts while the surface reaction between ethylene and oxygen in Equation 4.3 is the rate limiting step for 1%Cu-15%Ag/α-Al₂O₃ catalysts.

XPS was carried out before and after a reduction in pure hydrogen to further investigate the unique behavior of the 1%Cu-15%Ag/α-Al₂O₃ under a more reducing environment. XPS spectra for the two conditions for the Ag 3d and Cu 2p regions are shown in Figures 4.3 and 4.4, respectively.
The behavior of the catalyst under reducing conditions can be explained by the XPS results which show that the 1%Cu-15%Ag/α-Al₂O₃ material forms a surface alloy after reduction and is most likely phase separated at ambient conditions. Core level binding energy shifts in alloys have been shown to result mainly from valence electron hybridization and intra-atomic charge redistribution [213] and first principles calculations have predicted negative core level shifts for a number of binary fcc alloys including CuPd, AgPd, CuNi, NiPd, CuAu, PdAu, CuPt, and NiPt [214]. In other studies, it was found that the Ag d-band may either gain or lose electrons depending on the dilution of the alloy [215]. In a study of Ag rich AgPd nanoalloy oxygen reduction catalysts, it was found that the Pd 3d spectrum exhibited negative core
Figure 4.4: Cu 2p XPS spectra of a 1%Cu-15%Ag/α-Al₂O₃ before and after reduction level shifts regardless of the alloy stoichiometry but that negative shifts (or any shift) was only observed in the Ag 3d spectrum for Ag:Pd atomic ratios of less than 4 [216]. Rout et al observed a core level shift of -1.3 eV for Ag 3d and Cu 2p in a Ag₃Cu₃ bimetallic [217], although it should be noted that the Cu⁺ species was present in minute amounts in addition to metallic Cu.

Measurements of apparent activation energies for ethylene epoxidation and total combustion for 15%Ag/α-Al₂O₃ catalysts containing varying levels of Cu were made at two ratios, C₂H₄/O₂=1 and C₂H₄/O₂=5, as listed in Table 4.1. Ethylene oxide formation becomes much less activated under ethylene rich conditions (10% C₂H₄ + 2% O₂) as evidenced by the activation energy of the for the 1%Cu-15%Ag/α-Al₂O₃
catalyst changing from 28.5±4.8 kJ/mol to 11.4±1.6 kJ/mol, which is indicative of an active site change. As such, the results from the kinetic analysis, reaction parameter sweep, and XPS together suggest that a Cu-Ag surface alloy is forming for the 1%Cu-15%Ag/α-Al₂O₃ catalyst under ethylene rich conditions which creates new active sites, changes the rate limiting step from oxygen dissociation to the surface reaction between ethylene and oxygen and converts more ethylene into ethylene oxide than under the oxygen rich condition.

The change from being rate limited oxygen dissociation is logical, as it is well known that ensemble effects in alloys can be important in dissociative chemisorption [218]. It should be noted that such a decrease in the ethylene oxide activation barrier was observed only for the 1%Cu containing catalyst and other Cu loadings remained constant, within error, at both feed compositions. Also of interest is the favorable activation barrier of the 0.2%Cu-15%Ag/α-Al₂O₃ at both feed gas compositions. Specifically, at a C₂H₄/O₂ of 1 the activation barrier for epoxidation was measured to be 19.5±2.0 kJ/mol while the activation barrier for combustion was measured to be 40.3±3.7 kJ/mol. This is consistent with the superior ethylene oxide selectivity measured for the 0.2% Cu containing catalyst shown in Figure 4.1.

It is interesting to note that other loadings of Cu investigated for the 15%Ag/α-Al₂O₃ catalyst do not appear to exhibit alloying behavior under reducing conditions. A possible explanation is that CuOx may be harder to reduce at higher Cu loadings

<table>
<thead>
<tr>
<th></th>
<th>C₂H₄/O₂ Ratio = 1</th>
<th>C₂H₄/O₂ Ratio = 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ea (kJ/mol)</td>
<td>Ea (kJ/mol)</td>
</tr>
<tr>
<td>15%Ag</td>
<td>27.5±2.1</td>
<td>34.1±1.1</td>
</tr>
<tr>
<td>0.2%Cu-15%Ag</td>
<td>19.5±2.0</td>
<td>40.3±3.7</td>
</tr>
<tr>
<td>1%Cu-15%Ag</td>
<td>28.5±4.8</td>
<td>30.5±1.9</td>
</tr>
<tr>
<td>5%Cu-15%Ag</td>
<td>31.1±2.2</td>
<td>35.2±3.0</td>
</tr>
</tbody>
</table>
or that the Cu atoms may have arranged themselves at this loading into separate particles which are not properly juxtaposed with silver to alloy when reduced. In general, phase segregation of Ag and Cu would be expected to be exacerbated by higher Cu loadings and larger particle sizes [219] which provide plausible explanations for the lack of alloy formation at higher Cu loadings. At the 0.2% Cu level, it is possible that alloy formation is occurring under reduction conditions but that loading isn’t high enough to produce a discernable change in activity. Indeed, while it is difficult to understand the changes in Cu distribution at such small loadings, the SEM images in Figure 4.5 show dramatically different Ag particle morphologies when the Cu loading is changed. Figure 4.5 b) 0.2%Cu-15%Ag/α-Al₂O₃ catalysts show a mixture of small Ag rods and particles as well as larger agglomerates, while higher Cu loadings of 1 and 5% shown in c) and d), respectively, show an increasingly polydisperse size distribution. Conversely, the size distribution in Figure 4.5 a) 15%Ag/α-Al₂O₃ only is comparably much more monodisperse.

In general, the interplay between Ag size, shape and selectivity is complex. Most Ag/α-Al₂O₃ catalysts feature large (111) faceted Ag particles where increased particle sizes have been linked with higher EO selectivities due to a change in concentration of surface defects [220]. That being said, smaller particles with better coverage of the α-Al₂O₃ support have separately been credited with higher EO selectivities due to increased active surface area and blockage of unselective sites on the α-Al₂O₃ support [221]. Additionally, DFT predictions have suggested that the Ag(100) surface is intrinsically more selective than Ag(111) due to a higher disparity between activation barriers for epoxidation and combustion, in favor of epoxidation [222] and this has been verified experimentally by comparing the activities of nanospheres, nanocubes, and nanowires [223]. Thus, the unique rod-like morphology observed in the case of Figure 4.5 b) 0.2%Cu-15%Ag/α-Al₂O₃ warrants further investigation since it begs the question of whether the increased activity and more favorable activation barriers
Figure 4.5: SEM images of 15% Ag/α-Al₂O₃ catalysts with a) no Cu addition, b) 0.2% Cu addition, c) 1% Cu addition, and d) 5% Cu addition

listed in Table 4.1 is a consequence of the concentration and oxidation state of Cu creating a desirable surface structure and promotional effects or simply related to the unique Ag morphology which was formed in this case. It should be noted that in other experimental investigations of similar Cu and Ag loadings this type of morphology was not reported [66].

EDS scans of several randomly selected large (>500 nm) α-Al₂O₃ particles chosen from the SEM images of samples a-c shown in Figure 4.5 were collected to measure the actual loading of Ag and Cu on the support. The EDS measured Ag loading for the 15% Ag only catalyst was found to be 18±15.9 wt%, 29±15.3 wt% Ag and 0.15±0.18 wt% for the 0.2%Cu-15%Ag catalyst, and only 6.7±2.7 wt% Ag and 0.3±0.4 wt%
Cu for the 1%Cu-15%Ag catalyst. The large standard errors on these measurements is likely a result of real inhomogeneity of the catalytic material. In other words, the loading of Ag and Cu are quite high on certain $\alpha$-Al$_2$O$_3$ particles and quite low on others. Even so, certain insights can be made by evaluating this data. Notably, the 29±15.3 wt% Ag loading on the 0.2%Cu-15%Ag catalyst which is almost double the nominal loading shows that the distribution of Ag on the support is indisputably inhomogeneous. On the other hand, the 6.7±2.7 wt% Ag loading on the 1%Cu-15%Ag catalyst could either be a result of an inhomogenous distribution of Ag (ie. the Ag in the impregnation solution is present at higher loadings on other particles which were not measured) or simply a result of poor Ag uptake for this preparation condition. In order to corroborate the latter theory a bulk quantification of the elemental loadings, such as ICP-MS, would need to be performed. Additionally, it should be noted that neither SEM/EDS or XRD studies of the catalysts revealed the existence of separate Cu nanoparticles on any of the Cu promoted Ag/$\alpha$-Al$_2$O$_3$ catalysts. XRD patterns of the catalysts are shown in Figure 4.9 where the absence of any peaks which can be reference to metallic Cu, Cu(I) or Cu(II) oxide are noted.

4.2 Co-promoted X-Cu-Ag/$\alpha$-Al$_2$O$_3$ Catalysts

A number of co-promoters were added to the 0.2% Cu-15% Ag/$\alpha$-Al$_2$O$_3$ formulation which was found to be the optimum Cu-Ag stoichiometry for ethylene epoxidation under standard reaction conditions, as previously discussed. The preliminary screening involved sampling co-promoters which could either form stable alloys with Cu and/or Ag (ie. Au, Ru, Zn, Pt, Mg, Pd) or had been shown in previous work, experimental or theoretical, to catalyze or promote epoxidation (ie. Sn, Mo, Au, Pt, Cs, Pd, Re) [5, 13, 61, 66, 72, 77, 129, 224–229]. In a study of the ethylene epoxidation performance of Ag/SrTiO$_3$ catalysts promoted with Au, Ba, Pd, Sn and Cu promoters it was found that only Au, Ba, and Cu improved the ethylene oxide selectivity relative
to an Ag only catalyst [225]. Pd and Sn did not improve selectivity or activity but in the case of the Sn-Cu-Ag system, the stability of the catalyst was increased. The promotional effect of Sn in terms of improved catalyst stability was hypothesized to be a result of lowered rates of coke formation as evidenced by TG-DTA results [225]. These results were similar to those made by Bae et al who studied Sn promotion of the hydrodechlorination of CCl₄ over Pt-Sn/γ-Al₂O₃ and found that Sn improved stability by destroying the Pt surface sites linked to coking and transferring electrons to Pt such that the HC-Pt bond strength lessened [226]. In contrast to the findings of Chongterskool et al [225], who found that the addition of 0.63% Pd increased coking and ultimately decreased ethylene oxide selectivity, work by Dellamorte showed that 100 ppm Pd could potentially double the ethylene oxide selectivity when compared to a base silver catalyst, appearing to increase the rate of oxygen dissociation [5]. The discrepancy between these results is not entirely clear, but could perhaps be a result of the very different levels of Pd loading used. Furthermore, while Pd promotion and Cu promotion have each been studied for Ag/α-Al₂O₃ catalysts, the co-promoted system had not. Table 4.2 shows the co-promoters which were part of the initial screening as well as their corresponding loadings. Starting points in terms of impregnation sequence and promoter loading were based off the available literature data on each promoter. Details regarding the synthesis of the co-promoted catalysts is discussed in greater detail in the experimental section of this thesis.

Figure 4.6 shows the EO selectivity at 5±0.5% C₂H₄ conversion for the co-promoted 0.2% Cu-15% Ag/α-Al₂O₃ catalysts. Measurements were made with a 10% C₂H₄, 10% O₂, and balance N₂ feed at a space velocity of 4,000 h⁻¹ at temperatures between 230-350°C to achieve comparable conversion levels. Corresponding apparent activation energies for the co-promoted catalysts screened are shown in Figure 4.7.

Apparent activation energies for C₂H₄ consumption, epoxidation, and combustion for the co-promoted catalysts described above and listed in Table 4.2 are shown in
Table 4.2: Co-promoters screening for X-0.2% Cu-15% Ag/α-Al₂O₃ catalyst formulation

<table>
<thead>
<tr>
<th>Promoter</th>
<th>Ag (wt%)</th>
<th>Cu (wt%)</th>
<th>Promoter (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu-Mn-Ag</td>
<td>15</td>
<td>0.2</td>
<td>2000</td>
</tr>
<tr>
<td>Cu-Sn-Ag</td>
<td>15</td>
<td>0.2</td>
<td>250</td>
</tr>
<tr>
<td>Cu-Mo-Ag</td>
<td>15</td>
<td>0.2</td>
<td>100</td>
</tr>
<tr>
<td>Cu-Au-Ag</td>
<td>15</td>
<td>0.2</td>
<td>2000</td>
</tr>
<tr>
<td>Cu-Ru-Ag</td>
<td>15</td>
<td>0.2</td>
<td>2000</td>
</tr>
<tr>
<td>Cu-Zn-Ag</td>
<td>15</td>
<td>0.2</td>
<td>100</td>
</tr>
<tr>
<td>Cu-Pt-Ag</td>
<td>15</td>
<td>0.2</td>
<td>110</td>
</tr>
<tr>
<td>Cu-Cs-Ag</td>
<td>15</td>
<td>0.2</td>
<td>100</td>
</tr>
<tr>
<td>Cu-Mg-Ag</td>
<td>15</td>
<td>0.2</td>
<td>100</td>
</tr>
<tr>
<td>Cu-Pd-Ag</td>
<td>15</td>
<td>0.2</td>
<td>100</td>
</tr>
<tr>
<td>Cu-Re-Ag</td>
<td>15</td>
<td>0.2</td>
<td>75</td>
</tr>
</tbody>
</table>

Figure 4.6: EO selectivity at 5 ± 0.5% C₂H₄ conversion for co-promoted 0.2% Cu-15% Ag/α-Al₂O₃ catalysts
Figure 4.7: Apparent activation energies for ethylene consumption, epoxide formation, and combustion for co-promoted 0.2% Cu-15% Ag/α-Al₂O₃ catalysts measured between 230-350°C.

Figure 4.7. It’s interesting to note that the only co-promoted 0.2%Cu-15%Ag/α-Al₂O₃ catalyst which appeared to have more favorable kinetics for epoxidation was the Cs promoted material. Additionally, the catalyst with the highest selectivity at a 5% ethylene conversion level was much more activated than the base Ag catalyst.

Co-promoters from the initial screening were selected for further investigation with factorial design based on the criteria that they improved the ethylene oxide selectivity with respect to unpromoted Cu-Ag catalysts which included Cs, Re, Au, and Sn. Previous work involving the engineering of promoted alumina supported Cu-Ag and Ag catalysts has shown a tremendous sensitivity to the impregnation sequence and promoter loadings involved [61, 67]. For example, Dellamorte et al found that Re pro-
promoted Ag catalysts through a presumed defect site blocking mechanism, only at very small loadings (<50 ppm) and only when Re was sequentially impregnated onto the support [67]. As such, the parameters selected for continued investigation with simple $2^2$ factorial screening designs, were the co-promoter impregnation order on the catalyst and the promoter loading, as shown in Figure 4.8. Here, the notation Cu-(X-Ag) means that the co-promoter was impregnated with Ag, dried, calcined and reduced, and finally impregnated with Cu before an additional reduction. Similarly, the notation (Cu-X)-Ag simply implies a comparable procedure where the co-promoter was instead impregnated in the second impregnation step with Cu.

The XRD patterns of selected catalysts from the co-promoter screening design as well as unpromoted Cu-Ag and Ag only catalysts are shown in Figure 4.9. Here, it should be noted that the inclusion of the selected promoters neither effected the Ag oxidation state or the formation of Cu or Cu oxide particles, which are absent in all XRD patterns.

The grain sizes and d-spacing of the metallic fcc Ag were also determined for the Ag (111) plane from the XRD patterns as listed in Table 4.3. Grain sizes ranged from
25.7 nm in the 0.2%Cu-15%Ag/α-Al₂O₃ case to 41.0 nm in the case of Au promotion. The grain size of the Ag only catalyst was 31.4 nm. The d-spacings of Ag (111) were approximately 0.235 nm for all the catalysts, suggesting that promoters were not being incorporated into the Ag lattice or significantly influencing the lattice strain in the material.

4.2.1 Cs-Cu-Ag/α-Al₂O₃ Catalysts

Cesium is quite well studied as a promoter for Ag/α-Al₂O₃ ethylene epoxidation catalysts and has even been studied in detail as a potential promoter for the Cu-Ag system [230], where it was found that the promotional effects of Cs and 0.2%Cu were largely additive. Nonetheless, based on the enhanced ethylene oxide selectivity at
Table 4.3: Grain sizes and d-spacing for fcc Ag from XRD patterns of 0.2%-15% Ag/α-Al₂O₃ co-promoted with Au, Re, Cs, and Sn

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>d (Å)</th>
<th>Grain Size (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15%Ag/α-Al₂O₃</td>
<td>2.345</td>
<td>31.4</td>
</tr>
<tr>
<td>0.2%Cu-15%Ag/α-Al₂O₃</td>
<td>2.349</td>
<td>25.7</td>
</tr>
<tr>
<td>1%Cu-15%Ag/α-Al₂O₃</td>
<td>2.351</td>
<td>36.0</td>
</tr>
<tr>
<td>0.2%Cu-75ppmRe-15%Ag/α-Al₂O₃</td>
<td>2.349</td>
<td>43.2</td>
</tr>
<tr>
<td>0.2%Cu-(100ppmCs-15%Ag)/α-Al₂O₃</td>
<td>2.347</td>
<td>26.3</td>
</tr>
<tr>
<td>0.2%Cu-(250ppmSn-15%Ag)/α-Al₂O₃</td>
<td>2.349</td>
<td>36.7</td>
</tr>
<tr>
<td>(0.2%Cu-0.2%Au)-15%Ag/α-Al₂O₃</td>
<td>2.350</td>
<td>41.0</td>
</tr>
</tbody>
</table>

a 5% ethylene conversion level which was measured for the 0.2%Cu-(100 ppm Cs-15%Ag)/α-Al₂O₃ catalyst tested in the co-promoter screening shown in Figure 4.6 it was desirable to investigate this promoter further. The main objectives of completing this work were to establish the optimum prepartaion conditions for the 0.2%Cu-Cs-15%Ag/α-Al₂O₃ catalyst and gain an improved fundamental understanding of how Cs interacts with the 0.2%Cu-15%Ag/α-Al₂O₃ system.

**Effects of Cs impregnation order and loading on 0.2%Cu-15%Ag/α-Al₂O₃ catalysts**

The main effects of Cs loading and impregnation order for a Cs-0.2%Cu-15%Ag/α-Al₂O₃ catalyst on ethylene oxide selectivity at 5% C₂H₄ conversion are shown in Figure 4.10, as established from the aforementioned 2² factor screening design. As shown, the average effect of increasing the Cs loading from 50 to 150 ppm was to increase the ethylene oxide selectivity whilst co-impregnating Cs with Cu rather than Ag had the effect of decreasing the selectivity. It should be noted that the design was centered around the original starting point in the investigation of Cs loading pertaining to a 0.2%Cu-(100 ppm Cs-15%Ag)/α-Al₂O₃ catalyst and that this formulation was actually optimal in terms of EO selectivity as will be discussed in more detail subsequently.

Insights into the trends of ethylene oxide selectivity at 5% C₂H₄ conversion with
Figure 4.10: Main effects DOE analysis of Cs loading and impregnation order for a Cs-0.2% Cu-15% Ag/α-Al₂O₃ catalyst on the ethylene oxide selectivity at 5% C₂H₄ conversion respect to Cs loading and impregnation order can be made by comparing SEM images of the different catalysts, as shown in Figure 4.11 where it is evident that the average size of the Ag particles increases substantially when Cs is impregnated with Cu rather than Ag. The average size of Ag particles when Cs was co-impregnated with Ag was within error for the two Cs loadings, being 18.9±8.5 nm for a) Cu-(50 ppm Cs-Ag) and 15.7±0.8 nm for b) Cu-(150 ppm Cs-Ag). When Cs was instead impregnated with Cu the average size went up to 201±37.2 nm for c) (Cu-50 ppm Cs)-Ag and was much less when more Cs was co-impregnated with Cu for d) (Cu-150 ppm Cs)-Ag which had an average Ag size of 55.4±3.7 nm.

Overall, it was found that changing the impregnation order and loading of Cs on 0.2%Cu-15%Ag/α-Al₂O₃ had the effect of changing the Ag coverage on the α-Al₂O₃ support with the highest coverages being observed when Cs was co-impregnated with Ag rather than Cu. Additionally, increasing the Cs loading led to improved Ag
coverages even when the Cs is co-impregnated with Cu. The finding that Cs affects the Ag dispersion is consistent with reports by others where Cs has been suggested to act as a binder between Ag and $\alpha$-Al$_2$O$_3$, causing Ag to completely cover the support and possibly stabilizing the the Ag and $\alpha$-Al$_2$O$_3$ bond [221, 229]. The promotional effect based on this evidence is assumed to be one of unselective site blockage; less $\alpha$-Al$_2$O$_3$ support is exposed to catalyze the isomerization of EO to acetaldehyde and eventually CO$_2$. Thus, the increased selectivities coinciding with higher Ag coverages on the support observed in this work could plausibly be attributed to acid site blockage on the $\alpha$-Al$_2$O$_3$ surface.

With that said, a large amount of work suggests that cesiums promotional effect is actually an electronic one where Cs decreases the rate of EO combustion [231, 232]. With this in mind, perhaps the most compelling piece of evidence is that Cs improves the selectivity of Ag based catalysts even for Ag(111) single crystal studies [233]. In addition, a number of studies by Monnier and co-workers support that the Cs promotional effect for Ag catalyzed epoxidations is electronic, but that the effect is mainly a lowered desorption energy of the epoxide surface species due to the polarizability of the alkali cation [85, 234, 235].

Carrying out activity and kinetic experiments for 0.2%Cu-(Cs-15%Ag)/$\alpha$-Al$_2$O$_3$ catalysts with varied Cs loadings revealed that the optimum Cs loading was 100 ppm, which was the original starting point in the investigation of Cs loadings. As shown in Figures 4.12 and 4.13, 100 ppm Cs had the highest C$_2$H$_4$ conversion and ethylene oxide selectivity, as well most favorable activation barriers with respect to the two products. The different activation energies in Figure 4.13 evidence an active site change, suggesting that the main effect of Cs promotion on the Cu-Ag catalysts is not purely site blocking. Interestingly, the higher ethylene conversion measured for the optimum catalyst is not necessarily consistent with a hypothesis of an electronic promotional effect where one would expect the Cs to sit on the Ag nanoparticle
Figure 4.11: SEM images of 0.2%-Cs-15% Ag/α-Al₂O₃ catalysts with a) co-impregnation of 50 ppm Cs with Ag, b) co-impregnation of 150 ppm Cs with Ag, c) co-impregnation of 50 ppm Cs with Cu, and d) co-impregnation of 150 ppm Cs with Cu

surface where it would undoubtedly block sites which would otherwise be converting ethylene.

Analysis of the Ag 3d XPS spectra of Cs and Cu containing catalysts, shown in Figure 4.14 containing 15%Ag/α-Al₂O₃ catalysts shows that the Ag 3d₅/₂ binding energy is just 365.1 eV for the (100 ppm Cs-15%Ag) catalyst. This is much lower than what was observed in the case of 15% Ag only (367.3 eV), 0.2% Cu-15% Ag (367.6 eV) and 0.2% Cu-(100 ppm Cs-15% Ag) (367.8 eV). This indicates a very large amount of electron transfer from Cs to Ag and is consistent with what has been observed by
Figure 4.12: Selectivity and conversion of 0.2%Cu-(Cs-15%Ag)/α-Al₂O₃ catalysts at Cs loadings from 50-150 ppm

Diao et al made similar observations for Cs promotion of Ag catalysts and surmised that the EO selectivity was increased as Cs was aiding in EO desorption from the Ag catalyst [61]. Conversely, the increases in binding energy when Cu is added means that Cu is transferring electron density away from Ag which could affect the reactivity of adsorbed O₂. It is an interesting point that the Cu and Cs affect Ag 3d binding energy differently, suggesting that a balance between the two may be critical for optimal catalyst performance. Overall, the XPS results substantiate claims made by others that the polarizability is indeed a factor in the promotion of the Ag catalyzed epoxidation, but does not rule out the possibility of a concomitant binding effect, as discussed previously.
Effect of Cu loading on Cu-(100 ppm Cs-15% Ag)/α-Al₂O₃ catalysts

Figure 4.15 shows how ethylene oxide selectivity is affected by changing the Cu loading on a (100 ppm Cs-15% Ag)/α-Al₂O₃ catalyst, where all samples were tested between 230-300°C with a 10% O₂, 10% C₂H₄ feed in balance N₂ feed. This experiment was carried out using 100 ppm Cs co-promotion based on the optimization of Cs loading discussed previously. Adding 0.2% Cu to the (Cs-Ag) formulation increased selectivity to 50% but further addition of Cu had a detrimental effect on activity, with 5% Cu almost outweighing the benefit of Cs promotion on the base Ag completely. This trend is selectivity, together with the results from XPS showing that Cu and Cs have
Figure 4.14: Ag 3d XPS spectra 15%Ag/α-Al₂O₃, (100 ppm Cs-15%Ag/α-Al₂O₃,0.2%Cu-15%Ag/α-Al₂O₃, and 0.2%Cu-(100 ppm Cs-15%Ag/α-Al₂O₃ catalysts opposing effects in terms of electron transfer to and from the active sites, suggest that higher EO selectivity may be afforded for the 1% Cu through the addition of more Cs.

Adding 100 ppm of Cs had the effect of increasing the selectivity of the Cu-15%Ag/α-Al₂O₃ catalysts for all loadings of Cu investigated. As previously shown, the polydisersion of the Ag particle size increased dramatically as the Cu loading was increased on a 15%Ag/α-Al₂O₃ catalyst. When this morphology is compared to the morphology when Cs is present, as shown in Figure 4.16 it can be seen that the addition of 100 ppm Cs greatly improved the dispersion of the Ag particles on the support. This is a possible explanation for the increased activity of the Cu-15%Ag/α-Al₂O₃ catalysts when Cs was used as a co-promoter, as discussed previously.
Figure 4.15: Effect of Cu loading on ethylene conversion and ethylene oxide selectivity for a 100 ppm Cs-15%Ag/α-Al₂O₃ catalyst

Figure 4.16: SEM images of Cu-(100 ppm Cs-15% Ag)/α-Al₂O₃ catalysts with a) no Cu, b) 1% Cu, and c) 5% Cu addition
4.2.2 Sn-Cu-Ag/α-Al$_2$O$_3$ Catalysts

In contrast to Cs, there are relatively few studies where Sn has been investigated as a component of epoxidation catalysts. Extremely promising reports of high activity and stability for a 0.32% Sn-1.39% Cu-17.16% Ag/SrTiO$_3$ catalyst where EO selectivity was 95.1% and coke formation was only 2.9% after 72 hours on stream from Chavadej and co-workers [225] together with the favorable selectivity we measured for the 0.2%Cu-(250 ppm Sn-15%Ag)/α-Al$_2$O$_3$ catalyst tested in the co-promoter screening shown in Figure 4.6 led to the further investigation and optimization of Sn co-promotion. The main objectives of completing this work were to establish the optimum prepartaion conditions for the 0.2%Cu-Sn-15%Ag/α-Al$_2$O$_3$ catalyst and gain an improved fundamental understanding of how Sn interacts with the 0.2%Cu-15%Ag/α-Al$_2$O$_3$ system.

Effects of Sn Impregnation Order and Loading on 0.2%Cu-15%Ag/α-Al$_2$O$_3$ Catalysts

The effects of Cs loading and impregnation order for a Sn-0.2% Cu-15% Ag/α-Al$_2$O$_3$ catalyst on ethylene oxide selectivity at 5% C$_2$H$_4$ conversion are shown in Figure 4.17. The average effect of increasing the Sn loading from 50 to 450 ppm was to decrease the ethylene oxide selectivity whilst co-impregnating Sn with Cu rather than Ag had the virtually no effect on selectivity.

Maximum selectivity and the activation barriers for epoxidation and combustion for 0.2%Cu-(Sn-15%Ag)/α-Al$_2$O$_3$ catalysts with varied Sn loadings are shown in Figures 4.18 and 4.19, respectively. The highest EO selectivity was measured for the 0.2%Cu-(50 ppm Sn-15%Ag/α-Al$_2$O$_3$ catalyst, which corresponded to the lowest loading of Sn investigated. It can also be seen from the kinetic experiments, the results of which are shown in Figure 4.19 that the 50 ppm Sn catalyst was the only catalyst of the three which had favorable kinetics for EO formation as evidenced by the lower
Figure 4.17: Main effects DOE analysis of Sn loading and impregnation order for a Sn-0.2% Cu-15% Ag/α-Al₂O₃ catalyst on the ethylene oxide selectivity at 5% C₂H₄ conversion.

EO activation barrier when compared to the combustion activation barrier for that point. This type of kinetic behavior is difficult to achieve over Ag catalysts which usually have nearly activation energies for the two reactions.

An interesting result from the DOE analysis of Sn-Cu-Ag catalysts is the inconsequence of the order of Sn impregnation on the catalyst activity, which could potentially mean that the promotional effect of Sn is completely unrelated to it’s proximity to Ag or Cu during the nucleation and growth of the nanoparticles. This is not to say that Sn doesn’t affect the migration of the two other components, but that the same effect is imparted regardless of the order of addition to the catalyst. Examination of TEM images of the catalysts in question (Figure 4.20) show a distinct porous morphology which is featured across all Sn loadings and impregnation schemes studied.

EDS analysis of the porous agglomerates (Figure 4.21 confirm that the structures are comprised of all three elements of interest; Ag, Sn, and Cu, where levels of Sn are
Figure 4.18: Selectivity and conversion of 0.2%Cu-(Sn-15%Ag)/α-Al₂O₃ catalysts at Sn loadings from 50-450 ppm

high enough to suggest that all of the Sn added to the catalyst lives in the porous strctures rather than the smaller Ag particles. The EDS measured composition of the porous structure based on 3 distinct regions was as follows: 20.9±3.5 wt% O Kα, 11.1±2.4 wt% Al Kα, 65.9±6.0 wt% Ag Lα, 1.24±0.02 wt% Sn Lα, 0.91±0.09 wt% Cu Kα. It is peculiar that the porous morphology only appears for Cu-Ag catalysts which contain Sn, since it is only added at ppm levels. Furthermore, even Ag-Sn only catalysts are lack this type of morphology, which means that all three elements are nescessary for its formation. Since 50-450 ppm Sn alone is not voluminous enough to create such a large morphohology change from its migration, it is logical to assume that Sn is affecting the mobility of Cu, Ag, or both.

This type of morphology is comparable to that formed via the Kirkendall Effect in mixed metal oxides, where the pores arise due to the boundaries between metals with
Figure 4.19: Activation energies of epoxidation and combustion for 0.2%Cu-(Sn-15%Ag)/α-Al₂O₃ catalysts at Sn loadings from 50-450 ppm

varied diffusion rates [236–240]. A similarity also exists with morphologies formed via galvanic replacement reactions where hollow structures are formed when a metal template dissolves and a second metal is deposited [240]. An analogous process may be facilitated by Sn between metallic Ag and the copper nitrate precursor used in synthesis. The logical issue is that in galvanic replacement reactions the metal being replaced typically has a high standard reduction potential that the replacement metal, which is not the case with Cu And Ag. The standard reduction potential is +0.80 eV for Ag⁺ and +0.34 for Cu²⁺. It is assumed that the process could not happen in the reverse manner because the silver nitrate is added first and decomposed to form Ag nanoparticles prior to Cu addition. If this is not true and complete decomposition of the silver nitrate has not occurred, a galvanic replacement reaction between silver
Analysis of the Ag 3d XPS spectra of Sn and Cu containing 15%Ag/α-Al₂O₃ catalysts, shown in Figure 4.22 shows that the Ag 3d₅/₂ binding energy was 367 eV for the (50 ppm Sn-15%Ag) catalyst. This is a slightly negative shift from the Ag only catalyst which had a Ag 3d binding energy of 367.3 eV indicating that there is some electron transfer from Sn to Ag on the catalyst surface. This moderate amount of electron transfer is consistent with what was reported by Bae et al in their studies of Sn promotion in the hydrodechlorination of CCl₄ [226].
Figure 4.21: EDS scan of porous morphology on 0.2% Cu-(250 ppm Sn-15% Ag)/α-Al₂O₃ catalyst and SEM image showing selected area

**Effect of Cu loading on Cu-(50 ppm Sn-15%Ag)/α-Al₂O₃ catalysts**

Figure 4.23 shows how ethylene oxide selectivity is sensitive to the Cu loading on a (50 ppm Sn-15% Ag)/α-Al₂O₃ catalyst, where all samples were tested between 230-300°C with a 10% O₂, 10% C₂H₄ feed in balance N₂ feed. This experiment was carried out using 50 ppm Cs co-promotion based on the optimization of Cs loading discussed previously. Interestingly, adding any amount of Cu to the (50 ppm Sn-15% Ag)/α-Al₂O₃ catalyst was found decreased the ethylene oxide selectivity with (50 ppm Sn-15% Ag)/α-Al₂O₃ alone yielding the most desirable catalytic activity. This is interesting as Sn has not previously been investigated as an ethylene epoxidation promoter without the co-presence of Cu, to my knowledge. The only existing account of Sn usage in ethylene epoxidation catalysis involved the co-promotion with Sn and Cu of Ag on a SrTiO₃ support reported by Chongterdoonskul et al [225]. Another interesting feature that can be seen in Figure 4.23 is that the activity of the 0.2%Cu containing catalyst and the 1%Cu containing catalyst were virtually the same. This
Figure 4.22: Ag 3d XPS spectra 15%Ag/α-Al₂O₃, (50 ppm Sn-15%Ag/α-Al₂O₃, 0.2%Cu-15%Ag/α-Al₂O₃, and 0.2%Cu-(50 ppm Sn-15%Ag/α-Al₂O₃ catalysts suggests that perhaps the Sn is sucessfully stabilizing the Cu in the metallic state during standard reaction conditions and would warrant further investigation, if not for the overall poor selectivity of the Cu-Sn-Ag catalysts when compared to Cu-Ag and Sn-Ag only catalysts.

A notable result, shown in the TEM images in Figure 4.24 is that the porous morphology featured in every Sn containing 0.2%Cu-15%Ag/α-Al₂O₃ catalyst imaged is completely absent for all other Cu loadings investigated. It’s quite interesting that the complex chemistry between the Ag, Cu, and Sn leading to the formation of the porous morphology previously discussed is sensitive to the ratio between the Cu and Sn components, where higher Cu/Sn ratios mute the effect.
4.2.3 Re-Cu-Ag/α-Al₂O₃ and Au-Cu-Ag/α-Al₂O₃ Catalysts

Both Re and Au incorporation into a 0.2%Cu-15%Ag/α-Al₂O₃ catalyst were found to be favorable in terms of ethylene oxide selectivity as shown in the co-promoter screening shown in Figure 4.6. This was consistent with other works which have shown that Re and Au can promote epoxidation for Ag/α-Al₂O₃ or Cu-Ag/α-Al₂O₃ catalysts, where rhenium, in particular, has been quite heavily studied. Due to their promotion of the 0.2%Cu-15%Ag/α-Al₂O₃ system, these two materials were studied further to optimize preparation conditions for incorporation into a fully promoted material.
Interestingly, neither Re or Au impregnation order or loading were found to have a statistically significant effect on the ethylene oxide selectivity at 5% ethylene conversion when analyzed using the aforementioned 2^2 full factorial screening design. Also noteworthy is the absence of significant structural differences between Cu and Au promoted catalysts when compared to the Ag only material as shown in Figure 4.25. In Figure 4.25 a), the large particles between 500-1000 microns in size can be confirmed to be mostly $\alpha$-$\text{Al}_2\text{O}_3$ using EDX and do not present a structural anomaly of interest.
Taking the optimal loadings of Re and Au investigated in the initial screening design, the optimum Cu loading for each co-promoted 0.2%Cu-15%Ag/α-Al₂O₃ catalyst was investigated and shown in Figure 4.26. This experiment was also performed for Sn and Cs promotion, as discussed previously, and is shown here for convenience. It’s interesting to note that 0.2% Cu was the optimum loading in terms of epoxide selectivity at 5% ethylene conversion irrespective of the co-promoter (Re,Cs,Au,Sn) employed. This suggests that perhaps the interactions between the co-promoter and Ag as well as Cu and Ag is much more important that that between Cu and the co-promoter when considering the effect on activity.

4.2.4 Activity of fully promoted (Cu-Au)-Re-(Sn-Cs-Ag)/α-Al₂O₃ catalysts

Using the pre-determined optimum conditions for Cu loading and co-promoter (Sn, Cs, Re, Au) loading and impregnation sequence, an optimized so-called fully promoted, (Cu-Au)-Re-(Sn-Cs-Ag), catalyst was synthesized and evaluated. For purposes of comparison, formulations including just Au-Re-(Sn-Cs-Ag), Cu-Re-(Cs-Ag), and Re-(Cs-Ag) were synthesized as well. The purpose of synthesizing and comparing the fully promoted material to one containing only Re-(Cs-Ag) and Cu-Re-(Cs-Ag) was
to evaluate the efficacy of the more obscure promoting materials (Sn and Au) when compared to Re and Cs, which are expected to have a synergistic effect on epoxide selectivity. The results of this analysis are shown in Figure 4.27, where performance for the Ag only and Cu-Ag only materials are shown as well.

The fully promoted material was able to promote EO selectivity at 5% ethylene conversion to a much greater extent relative to all other materials studied. In addition, it’s intriguing that adding Cu to a Re-(Cs-Ag) material lowers the EO selectivity by approximately 10% while adding Cu to a Au-Re-(Cs-Sn-Ag) material increases the selectivity by more than 20%. It’s possible that Cu disrupts the synergistic promotional effect of Re and Cs usually observed in Ag catalysts and would be interesting to conduct further experiments examining reaction kinetics, catalyst morphology and sur-
face structure to understand why. On a similar note, further investigation into these factors could also be informative when considering the drastic increase in selectivity when Cu is added to the Au-Re-(Cs-Sn-Ag) material.

4.3 Conclusions

High-throughput experimentation and parallel $2^2$ factorial screening designs were used to survey the parameter space with respect to operating conditions and co-promoter type, loading, and impregnation sequence in the development of Cu-Ag/α-Al$_2$O$_3$ catalysts. Results suggest that the ideal loading of Cu on a 15% Ag/α-Al$_2$O$_3$ catalyst under reaction conditions of 10% ethylene + 10% oxygen ($C_2H_4/O_2=1$) at 1 atm is 0.2% by weight, where the catalyst would likely be comprised of Ag nanoparticles with Cu$_x$ oxide phase segregated on the Ag surface. At this loading, under these con-
ditions, this phase segregated Cu\textsubscript{x} oxide provides a promotional effect and increases the epoxide selectivity. Further increases in the Cu loading above 0.2%Cu were found to be detrimental for epoxide selectivity under standard reaction conditions. That said, for high ethylene feed fractions (C\textsubscript{2}H\textsubscript{4}/O\textsubscript{2}=5) a 1%Cu containing catalyst was found to increase selectivity dramatically. XPS and kinetic evaluation of the 1%Cu-Ag catalyst suggest that this effect is the result of a surface alloy formation under these conditions which makes the oxygen dissocation step much more efficient.

A wide co-promoter screening was completed where both conventional and non-conventional epoxidation promoting elements were investigated. The most promising candidates from the screening were found to be Au, Re, Sn, and Cs, which were each optimized in terms of their impregnation sequence and loading. It was found that these variables did not have a statistically significant effect on the morphology or activity of Re and Au containing catalysts, while differences in Sn and Cs containing materials were notable. Specifically, it was found that increased Cs loading and co-impregnation with Ag greatly improved the dispersion of Ag on the \(\alpha\text{-Al}_2\text{O}_3\) support. In the case of Sn, it was found that lower Sn loadings benefited EO selectivity while impregnation order made little difference. In addition, it was found that the 0.2%Cu-15%Ag at all Sn loadings and impregnation sequences investigated displayed peculiar porous agglomerates thought to arise due to effects of Sn on the mobility of Cu and Ag. A fully promoted (Cu-Au)-Re-(Sn-Cs-Ag)/\(\alpha\text{-Al}_2\text{O}_3\) catalyst was synthesized using the optimal impregnation sequence and loading for each co-promoter which had a measured EO selectivity of roughly 69% at 5% ethylene conversion which is more than double that of the Ag only catalyst evaluated at comparable conditions. An interesting caveat was that the same catalyst was 30% less selective toward EO when Cu was omitted from the formulation altogether. Further work elucidating the effect of Cu on the morphology, surface structure and kinetic behavior of the Au-Re-(Sn-Cs-Ag)/\(\alpha\text{-Al}_2\text{O}_3\) would be useful in determining the origin of this disparity.
Chapter 5

Ethylene Epoxidation over Ag-Exchanged Zeolites

A series of Ag-exchanged zeolites were tested for their efficacy as ethylene epoxidation catalysts under varied pretreatment conditions. This work was part of a collaboration which led to the following publication [241]. In this study, collaborators synthesized a Ag⁺-Exchanged large pore, low silica analogue of faujasite which will be referred to as Ag-LSX, having the composition Ag₉₆Al₉₆Si₉₆O₃₈₄·nH₂O and modified the structure post-synthesis with pressure and temperature treatments together with various pore-penetrating fluids.

Structural models for the Ag-LSX materials pre and post modification were derived using high-resolution synchrotron X-ray powder and single crystal diffraction which included the populations of Ag cations and water molecules in distinct sites. It was found that a post synthesis modification involving 1.4 GPa pressure and 150°C in EtOH led to a 47.4% reduction of Ag cations in the Ag-LSX pores and 40.8% increase in the number of water molecules. In addition, the choice of pore penetrating fluid used in the post synthesis modification step was found to influence the formation of zero-valent Ag nanoparticles on the Ag-LSX structures which in turn influenced the activity of the materials for ethylene epoxidation. Experiments performed to determine ethylene epoxidation activity of the Ag NP-Ag LSX hybrids will be discussed in this chapter of the thesis.
5.1 Catalytic Testing Procedure

Ag-LSX and Ag-LSX-P\textsubscript{EtOH} materials prepared both with and without heat treatment at 600°C were tested for their ethylene epoxidation activity in the previously described 16-channel high throughput reactor. A standard 15wt% Ag/\(\alpha\)-Al\(_2\)O\(_3\) ethylene epoxidation catalyst was prepared for comparative purposes via wet impregnation of a low surface area Saint Gobain \(\alpha\)-Al\(_2\)O\(_3\) (SA 5562, 0.95 m\(^2\)/g) into an aqueous solution of AgNO\(_3\), according to patent literature [242]. The catalyst was then dried at 80°C overnight, calcined at 450°C for 12 hours in air and reduced in 20% H\(_2\)/N\(_2\) at 350°C for 12 hours prior to catalytic testing. A similar synthesis method for Ag/\(\alpha\)-Al\(_2\)O\(_3\) has been reported previously [13].

50 mg of each catalyst was loaded into five channels of the 16-channel reactor and introduced to a 30 ml/min feed of 6% ethylene (C\(_2\)H\(_4\)), 10% O\(_2\) and balance N\(_2\). All channels share a common feed with equal flow splitting achieved through a capillary tube bundle. After allowing catalysts to reach steady state under these conditions for 36 hours, the ethylene epoxidation reaction was carried out between furnace set points of 150 and 300°C whilst monitoring catalyst bed temperatures with individual thermocouples. Flow rates were controlled with Brooks mass flow controllers and effluent concentrations of C\(_2\)H\(_4\) ethylene oxide (EO), and CO\(_2\) were measured in parallel using a Fourier-Transform Infrared (FTIR) imaging system using the apparatus and calibrations outlined in the experimental section of this thesis.

Subsequently, C\(_2\)H\(_4\) conversion, EO selectivity and CO\(_2\) selectivity were calculated based on the effluent concentrations and reaction stoichiometry. Multiple data points were collected in order to reduce signal-to-noise ratio and an error bar for each measurement is defined as the measurement standard error. Catalyst activity was also measured at 250°C after various pretreatments, including no pretreatment, an oxidative pretreatment (2 hours in 30 ml/min of 20% O\(_2\) in balance N2 at 450°C) and a reductive pretreatment (18 hours in 30 ml/min of 20%H\(_2\) in balance N\(_2\) at 250°C).
5.2 Catalytic Activity of AgNP-Ag-LSX Hybrids

The catalytic activity of the hybrid materials depends on (1) the post-synthetic conditions used, such as heat treatment at 600°C, and pressure treatment in the presence of ethanol and (2) the specific reaction conditions studied, such as reaction temperature and pretreatment conditions. For all catalysts, ethylene conversion increased with increasing temperature and remained under 5% at temperatures below 220°C, as shown in Figure 5.1. Spline line fitting was used between experimental points on Figure 5.1 to guide the eye. Ag-LSX-P$_{EtOH}$ exhibited the highest C$_2$H$_4$ conversion with 23.3±0.6% conversion at 275°C, whereas Ag-LSX showed the lowest conversion at just 3.9±0.2% at 303°C. Conversely, Ag-LSX displayed the highest conversion among the four catalysts when the furnace set points were decreased to 150°C. Ag-LSX-600°C was the most selective catalyst studied, achieving 29.2±4.9% EO selectivity at 146°C at a 1.2±0.1% conversion rate, as shown in Figure 5.2. With the exception of the reaction data collected at 200°C, Ag-LSX-600°C consistently showed higher EO selectivity than the standard base 15% Ag/α-Al$_2$O$_3$ catalyst. While Ag-LSX and Ag-LSX-600°C were found to exceed the selectivity of the base 15% Ag/α-Al$_2$O$_3$ under certain conditions, Ag-LSX-P$_{EtOH}$ and Ag-LSX-P$_{EtOH}$-600°C were on average less selective than all other catalysts studied, with Ag-LSX-P$_{EtOH}$-600°C achieving a maximum selectivity of just 10.9±4.8% EO selectivity and 3.0±0.54% C$_2$H$_4$ conversion at a bed temperature of 209.17°C.
Figure 5.1: Ethylene conversion of Ag-exchanged zeolites during ethylene epoxidation
Catalyst performance at 250°C was found to depend on whether the catalysts were exposed to an oxidative or reductive environment prior to testing, as shown in Figures 5.3 and 5.4. Figure 5.3 shows that the conversion increased significantly for all catalysts after an 18 hour reductive treatment at 250°C with the lowest conversions being reached when no pretreatment was used. Contrary to the results for the untreated and pre-calcined catalysts, where Ag-LSX-P_{EIOH} achieved the highest conversion at 250°C, Ag-LSX-600°C converted the most C_2H_4 after the reductive pretreatment, reaching 41.0±2.3%. Ag-LSX reached 10.8±4.1% selectivity after the oxidative pretreatment, but this value dropped to 4.4±1.1% after the reductive pretreatment. Ag-LSX-600°C followed a similar trend, reaching 9.6±2.2% after calcination and decreasing to 7.7±0.6% after reduction. All other catalysts behaved differently, reaching their maximum selectivity after the reductive pretreatment.
The highest selectivity achieved throughout all pretreatment experiments at 250°C was 12.2±0.4%, which was achieved by Ag-LSX-P$_{EIOH}$-600°C after the reductive treatment.

![Figure 5.3: Effect of reductive and oxidative pretreatment on C$_2$H$_4$ conversion of Ag-exchanged zeolites during ethylene epoxidation](image-url)
5.3 Conclusions

Tests of the catalytic reactivity and selectivity for ethylene epoxidation of the Ag/Ag-LSX hybrids clearly establishes the relevance of post-synthetic modifications to catalyst performance, where different morphologies were found to impart an effect on reactivity. It was found that above a reaction temperature of 225°C, the post-synthetic treatment with pressure only resulted in the highest C$_2$H$_4$ conversion and EO selectivity, which was comparable to that measured for a 15% Ag/α-Al$_2$O$_3$ catalyst. Additionally, it was found that the crystallinity loss in the hybrid after heating to temperatures above 600°C led to a reduction in C$_2$H$_4$ conversion rate to the level of the 15% Ag/α-Al$_2$O$_3$ catalyst and other post-synthetically modified hybrids.

The results indicate that the exploration of post-synthetic modifications of cation
substituted zeolites using pressure and temperature provides an alternative pathway
to the preparation of new heterogeneous metallic nanoparticles supported on zeolites,
suitable for use in heterogeneously catalyzed reactions such as ethylene epoxidation.
Further in situ treatment of the catalysts revealed that a prolonged reduction over
18 hours at 250°C results in significant changes of the conversion rates. In particular,
the C\textsubscript{2}H\textsubscript{4} conversion rate increased for the heat treated Ag-LSX-600°C as well as
the pressure-treated Ag-LSX-P\textsubscript{EIOH} and pressure and heat treated Ag-LSX-P\textsubscript{EIOH}-
600°C, while maintaining selectivity toward ethylene oxide.
CHAPTER 6

DEVELOPMENT OF DOPED MoVNb BASED ETHANE
PARTIAL OXIDATION CATALYSTS

This chapter deals with the incorporation of dopants at varied levels into Mo$_8$V$_2$Nb$_1$ catalysts including Pd, Ni, Ti redox elements and K, Cs, Te acid elements with the purpose of tailoring the acid and redox functionality of the material. Ultimately, the objective of this work is to address the effects of adding acid and redox elements in various ratios to elucidate their coupled effects on both ethane partial oxidation and their structural properties to gain insight into the origins of enhanced activity.

6.1 SYNTHESIS OF DOPED Mo$_8$V$_2$Nb$_1$ CATALYSTS

The formation of a uniform solid solution of the Mo-V-O oxide has been widely reported to be lead to the preferential oxidation of alkanes to olefins and acids. In contrast to conventional mixtures of molybdenum and vanadium based oxides, which give rise to multiple oxide phases due to phase segregation, the high dispersion of the vanadium in the Mo-V-O complex is achieved via the formation of a solid solution. Furthermore, the Mo-V-O complex allows for the incorporation of stabilization agents and promoters. Niobium has been reported as a stabilizing agent in the Mo-V-O structure, helping keep the vanadium and molybdenum species stable throughout the reaction [96, 102, 105, 106] by facilitating their redox cycles. The solid solution is due to the formation of an Anderson-Type complex, which is formed upon mixing the molybdenum and niobium precursors to create a (NH$_4$)$_3$NbMo$_6$H$_6$O$_{24}$ complex.
The Anderson-Type complex then readily reacts with VOSO$_4$ to form the Mo-V-M-O structure, where M here is niobium, and forming a solid solution with no observable phase segregation of the individual oxide phases.

A composition of Mo$_8$V$_2$Nb$_1$ was chosen as the basis for the DOE analysis due its high selectivity towards acetic acid and ethylene during EPO [102, 105]. Additionally, the excess molybdenum in the synthesis gel, where the Anderson-Type complex requires a stoichiometry of six to one Mo:Nb, serves to accommodate the addition of dopants into the base Mo$_8$V$_2$Nb$_1$ structure. The dopants for this work were chosen to probe the relationship between surface acidity and reducibility and EPO product distribution [97, 109]. In this study, the reducible metals chosen included palladium, nickel, and titanium. Each of these dopants varies in terms of their reducibility with palladium being the most reducible and titanium being the least. Additionally, these metals have been shown to promote EPO to favor the production of ethylene or acetic acid, both being target products for this system. In a similar manner, the surface acidity was adjusted by introducing potassium, cesium, or tellurium to the catalyst precursor. These elements were chosen to cover a range of acidities, where potassium represents a typical alkali group metal of nominal acidity and cesium represents a much stronger acid. Tellurium was chosen due to its precedence in catalyzing EPO to promote greater catalytic activity and the more selective formation of acetic acid [103, 110, 112].

To address mixed findings in the literature over the effect of the surface acidity and reducibility balance, we systematically varied the redox/acid element ratio between the acid elements and the redox elements to various degrees. Since the redox elements tend to affect catalytic activity largely by electronic effects caused by the electron orbital overlap from the d-shells of the transition metals, typically only small amounts of these elements are required to significantly change the catalytic activity. Conversely, acids affect catalytic activity by changing the surface acidity, where an
Table 6.1: Parameter space for the 3 level-4 factor full factorial design ($3^4$)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Variable</th>
<th>Low</th>
<th>Center</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Redox element (R)</td>
<td>Categorical</td>
<td>Pd</td>
<td>Ni</td>
<td>Ti</td>
</tr>
<tr>
<td>B: Acid/base element (A)</td>
<td>Categorical</td>
<td>K</td>
<td>Cs</td>
<td>Te</td>
</tr>
<tr>
<td>C: Dopant to host ratio (D/H)</td>
<td>Numerical</td>
<td>0.005</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>D: Redox to acid ratio (R/A)</td>
<td>Numerical</td>
<td>0.005</td>
<td>0.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Catalyst composition: $\text{Mo}_8\text{V}_2\text{Nb}_{1(1=H)}[R_{R/A}]D$

effect on catalytic activity is generally only observed at higher doping levels.

6.1.1 Parameter space

To explore all possible combinations between redox elements and acid elements 81 distinct catalyst formulations were prepared by adding nine unique dopant pairs to the base $\text{Mo}_8\text{V}_2\text{Nb}_1$ catalyst and synthesizing catalysts including each dopant pair at nine distinct loadings. Dopant pairs included the following: PdK, PdCs, PdTe, NiK, NiCs, NiTe, TiK, TiCs, and TiTe. The balance between redox and acid functionality is tailored by varying the redox to acid (R/A) ratio and the total amount of dopant added is varied with the dopant to host (D/H) ratio, where each were treated as numerical variables ranging from 0.005, 0.5, and 1.0, as summarized in Table 6.1. The addition of dopants at different levels can yield varied effects ranging from predominantly electronic interactions at low D/H ratios to complete phase segregation of the dopant species and possible formation of new active sites at high D/H ratios. It follows that the wide range of dopant/host ratios screened was intended to cover the range of these possible effects. Elemental ratios were relative to the niobium loading of the base catalyst (Nb=1), where the sum of the both redox and acid species totals to either a dopant to host ratio (D/H ratio) of 0.005, 0.5, and 1.0. For illustration, a D/H and R/A ratio of 1.0 corresponds to a composition of $\text{Mo}_8\text{V}_2\text{Nb}_{1}\text{Ni}_{0.5}\text{Te}_{0.5}$. The standard orders corresponding to each catalyst formulation are listed in Table 6.2 for reference.
Table 6.2: Standard orders corresponding to 3 level-4 factor full factorial design \((3^4)\) for doped Mo\(_8\)V\(_2\)Nb\(_1\) catalysts

| R/A=.005   | D/H=.005 | 1 | 10 | 19 | 28 | 37 | 46 | 55 | 64 | 73 |
| R/A=.005   | D/H=.5   | 2 | 11 | 20 | 29 | 38 | 47 | 56 | 65 | 74 |
| R/A=.005   | D/H=1    | 3 | 12 | 21 | 30 | 39 | 48 | 57 | 66 | 75 |
| R/A=.5    | D/H=.005 | 4 | 13 | 22 | 31 | 40 | 49 | 58 | 67 | 76 |
| R/A=.5    | D/H=.5   | 5 | 14 | 23 | 32 | 41 | 50 | 59 | 68 | 77 |
| R/A=.5    | D/H=1    | 6 | 15 | 24 | 33 | 42 | 51 | 60 | 69 | 78 |
| R/A=1    | D/H=.005 | 7 | 16 | 25 | 34 | 43 | 52 | 61 | 70 | 79 |
| R/A=1    | D/H=.5   | 8 | 17 | 26 | 35 | 44 | 53 | 62 | 71 | 80 |
| R/A=1    | D/H=1    | 9 | 18 | 27 | 36 | 45 | 54 | 63 | 72 | 81 |

6.2 Structural Characterization of Doped Mo\(_8\)V\(_2\)Nb\(_1\) Catalysts

6.2.1 EDS elemental uptake analysis

The hydrothermal synthesis method employed proceeds through the formation of an Anderson-Type heteromolybdate intermediate for which the possibility of incomplete element uptake exists. Furthermore, variation in elemental composition over the design space was intended by varying R/A and D/H ratio. Thus, EDS was used to both probe both intended and unintended variation in the loadings of catalyst components. Details of the experimental collection and analysis of EDS data is outlined in the experimental section of this thesis.

In particular, analysis of the EDS data was focused on disturbances to the base structure as evidenced by the measured vanadium and niobium contents. It should be noted that nominal loadings for the 81 catalysts were expected to fall in the
following range: Mo$_8$V$_2$Nb$_1$R$_{0.00025-0.5}$A$_{0.0025-1}$. Over the 81 samples studied, atomic loadings for the Mo$_8$V$_2$Nb$_1$ base composition were found to range from 1.28± 0.1 to 3.33± 0.84 for vanadium and 0.69± 0.12 to 1.17± 0.05 for niobium. While some of this variance can be ascribed to EDS measurement error, certain relationships between the base catalyst uptake and the catalyst design variables were found to be statistically significant. For instance, uptake of both vanadium and niobium into the structure were negatively correlated with increased D/H ratio, meaning that, to some extent, the dopants displaced the V and Nb from the material. It should be noted that this effect was more pronounced in the case of Nb, with Nb uptake being almost 10% less when D/H was increased from 0.005 to 1. This effect was also much more significant when the elements being doped were primarily redox elements (ie. high R/A ratio), as shown in Figure 6.1. This suggests that the redox elements were able to displace the niobium in part from the channels of the base structure.

Additionally, some sensitivity was found in terms of Nb and V uptake with respect to the specific redox and acid elements doped. V uptake was found to be particularly sensitive to the doping of redox elements, being the lowest when Pd was doped, while Nb uptake was sensitive to both redox and acid doping, with the lowest uptakes corresponding to Ti and Te doping. In general, the least amount of disturbance to the base structure was achieved when balanced levels of redox and acid elements were doped (R/A=1) and the greatest amount of disturbance was found at the highest doping levels (D/H=1). Additionally, an interaction between R/A ratio and D/H ratio was observed where increasing D/H ratio only caused significant changes to the base structure for high levels of redox element loading (R/A=1). This indicates that acid/base elements were more easily incorporated into the base structure than redox elements. Overall, it was found that increasing or decreasing D/H and R/A ratios yielded the intended variations in dopant loadings.
6.2.2 Crystalline structure of doped Mo$_8$V$_2$Nb$_1$ catalysts

The crystalline structure of the redox and acid/base element doped MoVNb catalysts were studied for all samples using powder X-ray Diffraction (XRD) as discussed in the experimental section of the thesis. The hydrothermally synthesized base MoVNb catalyst, shown in Figure 6.2 showed the Mo-V-O mixed-oxide phase hallmarked by sharp 22° and 45° (0 0 l) reflections and a broad 27° reflection.

Based on literature [107, 108, 114], this Mo-V-O structure is ascribed to a slab-like structure comprised of both ordered and disordered crystallographic directions. Additional peaks could be ascribed to MoO$_3$, Mo$_6$V$_9$O$_{40}$ or Mo$_3$Nb$_2$O$_{11}$ [105]. To understand the influence of the redox and acid/base dopants as well as their relative and overall doping levels, differences between the hydrothermally prepared base MoVNb and doped MoVNb catalysts were studied. XRD patterns reflective of the
The analysis of the XRD data focused on both the position and the Full Width Half-Max (FWHM) of the main 22° peak to calculate the d-spacing and grain size of the Mo-V oxide. Additionally, crystal faceting of the primary slab-like Mo-V-O phase was analyzed by measuring the intensity ratio between the sharp 22° peak, showing the ordered crystallographic growth direction, and the disordered, amorphous peak at 27°. Previous work showed a correlation between the intensity of the 22° reflection and the specific activity for ethane ODH [107]. Additionally, it was found that secondary phases were formed on top of the base Mo-V-O structure when doped with certain redox and acid/base elements at varying levels. The identity of these secondary phases are assorted Mo and V based oxides of different stoichiometry as well as, in a few cases, reflections from small particles of segregated oxides of redox/acid/base...
Figure 6.3: XRD pattern of the 81 hydrothermally prepared doped MoVNbOx catalysts

dopants. While exhaustive structural resolution of each design point was out of the scope of this study, the conditions under which secondary phase formation occurred were noted and relative intensities between the main reflection and the most intense peak arising from secondary phases were calculated to indicate the relative volume of the catalyst involved in secondary phase formation.

First, the d-spacing of the mixed oxide indicated by the peak location of the 22° reflection \( (d=4.01 \text{ Angstrom}) \) was tracked for each sample as a possible gauge for dopant incorporation directly into the mixed oxide lattice. In such a situation an increase in d-spacing (evidenced by a peak shift to lower 2θ) would be expected, since most dopant elements have large radius compared with Mo, V and Nb. It was
found, however, that the d-spacings of the 22° reflection for the doped samples only ranged from 3.98 to 4.02. This small range of d-spacings supports the conclusion that the various redox and acid/base dopants investigated were not actually incorporated directly into the mixed oxide lattice and most likely reside in the six and seven membered rings formed by the Mo-V-O structure, where these vacancies allow for the insertion of atoms [115].

The grain sizes, calculated from the FWHM of 22° peak, of the doped MoVNb samples were found to be sensitive to the dopants and levels studied. This parameter was investigated to understand how different doping levels could change the active surface area and/or redox properties of the catalysts; effects which may be expected to accompany a change in Mo-V-O grain size. The grain size of the base MoVNb material, calculated using the broadening of the 22° peak according to Scherrer’s equation [148, 149] was 22 nm. Identical analysis of the doped MoVNb catalysts showed that grain sizes ranged from 12.4-35.0 nm depending on the design levels employed.

Statistical analysis of the relationship between doping elements and levels with grain size revealed that the most important factors for controlling grain size were the type of redox element and the D/H ratio, as well as the interaction between the two. It was found that doping with Ni increased grain size most significantly while Ti yielded grain sizes which were smaller, and on average, identical to that of the base MoVNb oxide. In general, increasing dopant levels had the effect of decreasing grain sizes, but at the lowest level of D/H=0.005, no notable difference could be seen between the grain sizes when Pd, Ni, or Ti was doped. In an analogous manner, differences between grain sizes of Pd, Ni, and Ti doped materials were only apparent at R/A ratios of 0.5 or greater. These interactions simply indicate that the different behavior of redox elements with respect to grain size were not apparent under the conditions where the redox elements were doped in the smallest amounts (ie. small D/H and R/A ratios). The observation of decreased grain sizes at higher dopant
Figure 6.4: XRD grain size differences for MoVNbNiCs catalysts at varied dopant levels

levels, as can be seen for the MoVNbNiCs family of catalysts at the R/A=0.5 level in Figure 6.4 leads to the question of whether one of the effects of the redox dopant is to impede the crystal growth of the primary mixed oxide phase.

The relative intensity of the ordered 22° reflection scaled to the intensity of the disordered 27° reflection was investigated as an indication of ordered preferential growth. For convenience, this will be referred to as the primary phase intensity ratio (PPIR). The base formulation of MoVNb was found to have a PPIR of 3.41. R/A and D/H ratios were found to affect the PPIR significantly, with increasing each having the effect of decreasing the PPIR. It was also found that the significance of the effect of changing the D/H ratio was most apparent at the low R/A level of
In practice, this means that the highest PPIR values, and the only values which were greater than the base catalyst PPIR, occurred for catalysts with both low overall dopant levels and high relative levels of acid/base dopant (D/H=R/A=0.005) as shown in Figure 6.5. Interestingly, the redox and acid/base elements doped were found to have virtually no effect on this measurement, meaning that nearly identical trends held for all redox-acid/base pairs studied.

The final structural descriptor studied via XRD analysis was the formation and relative volume of secondary phases. This variable is important in understanding trends in activity due to its direct relation to the abundance of the active Mo-V-O phase. For convenience, this will be referred to as the secondary phase intensity ratio.
Figure 6.6: Secondary phase formation in doped MoVNb catalyst library as calculated from XRD (SPIR) and is defined as the XRD intensity ratio between the largest secondary phase peak and the largest Mo-V-O primary phase peak at 22° 2θ. A comprehensive figure showing the effect of synthesis parameters on secondary phase formation is shown in Figure 6.6.

While the redox element doped, particularly when the element was Pd, affected the occurrence of secondary phases, it had no significant effect on the SPIR. The SPIR was found to be mostly sensitive to the type of acid/base element doped as well as the R/A and D/H ratios. Specifically, it was found that doping with Cs at the low R/A level of 0.005 yielded the highest SPIRs and this effect was increasingly apparent at higher D/H ratios. The effect of increased SPIR with decreased R/A
ratio and increased D/H ratio held for other redox-acid/base pairings as well, but at a much smaller magnitude. The effect of secondary phase formation when Cs was doped is illustrated in Figure 6.7.

6.3 Ethane Partial Oxidation on Doped Mo$_8$V$_2$Nb$_3$ Catalysts

The catalytic evaluation of the catalyst compositions guided by the statistical design were carried in a temperature range of 120°C-460°C with an ethane to oxygen ratio of 4:5. As the product distribution of the EPO reaction has been shown to be highly sensitive to residence time and temperature, a space velocity and temperature optimization was carried out for the base catalyst composition to maximize the production
of acetic acid. The optimal temperature and space velocity for acetic acid selectivity were found to be 450°C±10°C and 1200 hr⁻¹, respectively. These conditions were used in the analysis of the DOE catalyst, which is summarized in Figure 6.8, showing the selectivity towards each product. Due to the fact the product distribution is highly dependent on residence time, where a slight change in residence time shifts the product distribution to favor ethylene, the catalysts were first compared at different conversions with all other relevant variables held constant.

The product distribution at 450°C for all 81 doped Mo₈V₂Nb₁ catalysts is shown in Figure 6.8. Design of experiments was used to elucidate statistically significant relationships between design levels and product distribution. The analysis of effects
relevant to the catalytic activity is highlighted in Table 6.3, which shows the trends across the different redox and acid/base elements, the D/H ratio, and the R/A ratio. A main conclusion from this analysis is that each variable investigated; redox element, acid/base element, redox/acid ratio, and dopant/host ratio had significant effects on the ethane conversion and product distribution.

The single most important variable investigated for optimizing ethylene selectivity was the redox element used, with a significant sensitivity to the acid element co-employed. For instance, ethylene selectivity can be increased drastically simply by doping with PdTe rather than PdCs, which was detrimental to ethylene formation. Conversely, product distribution was largely insensitive to the acid dopant when the redox element being doped was Ti. Overall, ethylene selectivity was maximized by doping with NiTe at a D/H level of 0.5 and a R/A level of 0.005.

Acetic acid selectivity was optimized by doping MoVNb with TiK or TiTe at low R/A and D/H levels (D/H=R/A=0.005) but showed a high level of sensitivity to interactions between the parameters investigated. The most important relationship found was that between the redox element, the acid/base element, and the D/H ratio, as illustrated in Figure 6.9. AA selectivity was optimized at very low dopant levels (D/H=0.005) for PdK and NiTe dopant pairs whereas a large dopant level (D/H=1) optimized AA selectivity for the TiTe dopant pair, with these compositions performing remarkably better than other redox-acid dopant pairs at equivalent D/H.
Figure 6.9: Interaction between redox element, acid element, and D/H level for AA selectivity

levels. It also should be noted that the optimum acid dopant pair for Ti was different at each D/H level studied.

A low R/A ratio of 0.005 was found favorable for both ethylene and acetic acid selectivity, indicating that in both cases an excess of acid/base dopant is needed relative to the redox dopant. This is consistent with literature, where the incorporation of acid/base elements at an atomic ratio of 2:1 between V and the acid/base element has been shown to result in the increased formation of value added products in partial oxidation reactions [104, 243]. Surface acidity is thought to play a large role in the product selectivity, where acid sites promote the formation and subsequent desorption of acetic acid while ethylene preferentially forms and desorbs on reducible sites [97], such as those found on the redox elements. However, in this case, it was found that acid sites were also necessary for the formation of ethylene. The role of surface acidity also extends to other catalytic systems for the conversion of ethane into value added products, where in the oxidative dehydrogenation of ethane the inclusion of highly basic metals such as platinum lead to increased selectivity towards ethylene [92, 94]. It is well known that dopant effects can considerably affect catalytic activity when doping with transition metals due to the electronic interactions between the metals and the host oxide structure [94, 96, 102, 109, 113, 188].

Two distinct mechanisms are possible in the partial oxidation of ethane into ethy-
lene and AA. The first possibility is the direct oxidation of ethane via a CH$_3$CH$_2$O* intermediate species followed by the subsequent oxidation to acetic acid [89, 99, 105]; the second is the oxidation of an adsorbed ethylene species through a Wacker mechanism involving a surface X-O site which reacts with water to form a X-OHOOH site capable of converting ethylene to AA [97, 109]. In our findings, an increase in AA formation was generally coupled with an immediate decrease in ethylene, suggesting that AA was forming mainly through the oxidation of re-adsorbed ethylene via the Wacker mechanism. However, the possibility of parallel pathways cannot be ruled out entirely as the products were often co-produced.

### 6.3.1 Structure-activity relationships in EPO over doped Mo$_8$V$_2$Nb$_1$

While a small R/A ratio being favorable for both acetic acid and ethylene formation can be attributed in part to an excess of surface acidity being needed relative to redox properties, it should also be noted that small R/A levels were highly correlated with high primary phase intensity ratios (PPIR) introduced previously. In fact, at the low D/H and low R/A pairing, the PPIR was as much as four times greater than its value at other D/H and R/A combinations. This is consistent with observations of increased ethane oxidation activity at higher intensity ratios reported previously [107]. It follows that in addition to creating favorable surface acid properties for reactivity, an excess of acid dopant could play a role in extending the aspect ratio of the slab-like structure of the primary active Mo-V-O phase indicated by the PPIR.

On the other hand, smaller D/H levels (D/H=0.005) were preferable for acetic acid formation while intermediate levels were optimum for ethylene formation (D/H=0.5). It should be noted that high D/H levels were associated with smaller Mo-V-O grain sizes measured with XRD and lower V and Nb uptake into the base catalysts evidenced by EDS. These results suggest that control over product distribution may be afforded through catalyst stoichiometry and/or tuning of grain size. It is clear,
however, that a large displacement of V from the Mo-V-O structure is unfavorable for all value product yields, as this was observed to the greatest extent for high doping levels of Pd and Cs, which on average yielded the lowest selectivity towards both acetic acid and ethylene.

In fact, Cs was detrimental to ethylene and AA formation for all redox elements at all D/H and R/A levels, leading to the formation of almost exclusively total oxidation products. This is likely because Cs disrupts the structural integrity of the host, as evidenced by the above average formation of secondary phases visible in XRD. As the primary Mo-V-O phase, hallmarked by the characteristic 22°XRD peak, has been attributed to the preferential oxidation towards olefins and acids [107, 244], it is reasonable to assume that the destabilization of this phase and secondary phase formation induced by Cs would negatively affect activity through the loss of AA and ethylene selective sites or formation of combustion sites. This type of structural disturbance induced by dopant addition to the base Mo-V-O structure is markedly different from that observed by others, where activity has been found to increase with increased dopant concentrations accompanied by higher defect densities and more polydisperse crystallites [111]. The difference in observed structural effect is possibly due to the very large atomic radius of Cs in comparison to other dopants studied.

To address the finding that the doped MoVNb reached different levels of conversion at 450°C, the catalysts were compared according to their ethylene and acetic acid selectivity as a function of conversion in Figure 6.10. For convenience, catalysts are labeled by their standard orders according to the 3^4 full factorial design. The corresponding factorial design levels (dopants and loadings) for each design point are shown in Table 6.2. To understand how changing the conversion level changed the selectivity of the most promising materials, the optimum catalysts were compared at different conversions achieved by ramping the catalyst bed temperature between 250-
Figure 6.10: Ethylene and acetic acid selectivity vs. ethane conversion for all samples at 450°C.

550°C. Optimum catalysts were defined as those samples which reached the highest AA or ethylene selectivity at the highest possible ethane conversions at 450°C, as shown in Figure 6.10. The ethylene and acetic acid selectivity of the selected catalysts at varied conversions are shown in Figure 6.11. In general, ethylene selectivity decreased with increased conversion, corresponding to higher bed temperatures, while acetic acid selectivity increased. For most catalysts, acetic acid selectivity was maximized at conversions > 80% while ethylene selectivity was maximized at conversions < 20%.

6.4 Conclusions

In our studies, the optimal catalyst compositions for ethane partial oxidation to both acetic acid and ethylene with regards to the addition of redox and acid dopants to a base Mo₈V₂Nb₁ catalyst were identified. DOE methodology was implemented to gain statistically significant insights on the impact of tuning the balance between the acidity and redox behavior of the catalyst via the addition of the selected dopants and to identify useful trends to aid the design of mixed metal oxide EPO catalysts in
the future. Analysis was carried out to correlate the redox element loading (Pd or Ni or Ti) and acid element loading (K or Cs or Te) with the catalytic performance and structural integrity of the materials. It was found that across all catalyst compositions explored, an excess of surface acidity relative to the redox element (R/A ratio of 0.005) benefited both ethylene and acetic acid formation. Additionally, investigation of the total dopant level (D/H ratio) led to the finding that doping high levels of Ti optimized the selectivity for both AA and ethylene, while doping high levels of Ni and Pd led to the formation of combustion products. Overall, AA production was favored with TiTe doping while ethylene production was favored with NiTe doping. Additionally, it was found that Cs doped catalysts ubiquitously favored ethane combustion. The effects of dopant composition on the catalyst structure were elucidated, where the extent of phase segregation and incorporation of dopants into the base catalyst was most sensitive to the acid/base element doped, and the incorporation of cesium was found to trigger the formation of multiple secondary phases. Overall, tuning the balance between redox and acid elements doped into Mo$_8$V$_2$Nb$_3$ catalysts resulted in not only changes to the surface acidity and redox properties, but also induced a change in the bulk catalyst structure, the coupled effects of which were
found to ultimately determine the materials catalytic properties.
CHAPTER 7

DEVELOPMENT OF PAA FUNCTIONALIZED GOLD NANOPARTICLES FOR ALZHEIMER’S THERAPY

Previous work has demonstrated the ability of polyelectrolyte functionalized AuNPs can to inhibit Aβ aggregation at substoichiometric ratios [121]. This chapter is focused on extending our understanding of this impressive inhibition ability to PAA-AuNPs comprised of size controlled AuNPs with end tethered thiolated PAA polymers of controlled molecular weight.

Specifically, the work presented is part of a concerted effort between three research groups involving (I) the synthesis of PAA-AuNPs of controlled properties, (II) the evaluation of the AuNPs in Aβ aggregation assays, and (III) the development of a statistical thermodynamic model to understand early Aβ aggregation in the presence of nanoparticles. Herein, the methodology development relevant to (I) the synthesis of PAA-AuNPs of controlled properties will be described in detail and the effects of the PAA-AuNP properties on Aβ aggregation as evaluated using a central composite design will be discussed.

7.1 GOLD NANOPARTICLE SYNTHESIS

7.1.1 VALIDATION OF EXISTING GOLD NANOPARTICLE SYNTHESIS METHODOLOGY

In order to leverage the existing knowledge base of gold synthesis methodology existing in the literature and establish a starting point for continued experiments several well-known synthesis procedures were reproduced for validation purposes. The prece-
dural details of the selected methodologies are discussed in length in the experimental section [156, 160, 166] and a comparison of the actual vs the expected (reported) average diameters is shown graphically in Figure 7.1.

It’s immediately evident that the seeded methods reported by Jana et al [166] did not yield the expected results. While the Au diameter in the seed solution was close to the expected value of 3.5 nm, being 4.1±1.1 nm, the diameter of the Seeding A solution was more than 50% different than the expected value of 5.6 nm, being 8.9±2.8 nm. While the Seeding B and Seeding C solutions, which had average diameters of 7.9±1.9 nm and 17.8±1.5 nm, were acceptably close to the expected values, their morphologies were too polydisperse to be useful in continued experimentation, where a quasi-spherical shape was desirable.

The AuNPs synthesized using the Brust methodology [160] were found to be more than twice as large as the expected diameter, at 5±0.22 nm. Additionally, it was
found that the solution of small, thiol-capped AuNPs in an organic solution was very difficult to manipulate (eg. wash, precipitate by centrifugation, and extract to an aqueous phase) when compared with AuNPs stabilized with weaker capping agents such as citrate in aqueous solutions. For these reasons, the traditional Brust method was discarded in continued experimentation.

Conversely, the three methods reported by Liang et al [156] were found to be at most, 23% different than the expected values and had narrow size distributions of mainly quasi-spherical shapes. Additionally, the resultant samples were easily manipulated through repeat washes with DI water and precipitation with ultracentrifugation. For these reasons, these methods were pursued in more detail with the goal of establishing precise size control over the AuNP solutions.

### 7.1.2 Literature Based Factorial Screening Design

As discussed previously, the room temperature NaBH$_4$ assisted, thermal citrate, and reverse citrate methods reported by Liang et al [156] were found to have the best reproducibility and most desirable traits in terms of size range, morphology and ease of manipulation when compared to several other methods reported in the literature. Due to the high volume of work which has been carried out involving the synthesis of gold nanoparticles, it was possible to find numerous occurrences in academic research where these methodologies were manipulated to change the AuNP average size [156, 157, 161, 164, 245]. It was found that this was accomplished entirely through the manipulation of the concentration of HAuCl$_4$ in the solution together with the ratio between citrate and gold, henceforth referred to as the C/G ratio.

To maximize the transferrable knowledge from the aforementioned references, more than 60 experimental points were compiled and used to populate a statistical design such that gold nanoparticle size could be modeled as a function of HAuCl$_4$ concentration and C/G ratio. The resultant contour plot showing predicted AuNP
average diameter for the thermal citrate method is shown in Figure 7.2. It can be seen that for this method at all C/G molar ratios below 0.4, changing HAuCl$_4$ concentrations has little effect on the AuNP diameter with all diameters being $<5$ nm. Above a C/G molar ratio of 0.4 an interaction being C/G ratio and HAuCl$_4$ concentration is evident, where more moles of citrate are needed per mole of HAuCl$_4$ at higher HAuCl$_4$ concentrations. This interaction is probably due to the increased ionic strength of the solution at higher concentrations.

7.1.3 Modification of Existing Gold Nanoparticle Synthesis Methodology

Experiments performed as validation of literature reported AuNP synthesis methodology together with the factorial design analysis of thermal citrate literature data previously discussed served as guiding points for the further augmentation of AuNP
synthesis through room temperature NaBH₄ assisted, thermal citrate, and reverse citrate methods. In order to obtain the desired size controlled solutions of quasi-spherical AuNPs for evaluation as Aβ aggregation inhibitors, experiments changing the C/G ratio and/or the HAuCl₄ concentration within each of these methods were completed.

**Thermal Citrate Method**

The thermal citrate method is an excellent candidate in the fabrication of gold nanoparticle dispersions between 10 and 20 nm. In this work, a modified thermal citrate method was utilized based loosely off that reported by Liang et al [156]. Specifically, 0.001M HAuCl₄ was first heated to 100°C in de-ionized water (DIW), after which 5 ml of DIW containing trisodium citrate dihydrate was added at the following citrate:gold molar ratios: 10, 7.5, 5, 2.5, 1. The combined gold+citrate solution was then held at 100°C for 15 minutes, during which nucleation and nanoparticle growth commenced. Figure 7.3 shows the TEM images of the gold nanoparticles synthesized under thermal citrate conditions with varying citrate:gold molar ratios (denoted with C/G). It’s evident through simple visual inspection of TEM images that the nucleation and growth kinetics significantly changed upon reduction of the citrate:gold molar ratio to C/G=1. This condition provides poor control over dispersion as evidenced by a mixture of quasi-spherical particles <500 nm and faceted particles >500 nm. Size distributions generated from the average and standard deviation of particle sizes measured with CellProfiler are shown in Figure 7.4. At levels of C/G at or above 2.5, changing this ratio was adequate to vary particle size between 14.5±1.9 nm and 31.1± 5.7 nm. Tabulated results of particle size analysis for each experimental point carried out both manually and with CellProfiler are listed in Table 7.1.
Figure 7.3: TEM micrographs showing size and morphology of AuNPs synthesized with thermal citrate methodology and varied C/G ratio

Table 7.1: Sizes of AuNPs synthesized with thermal citrate method

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Figure 7.4: Size distributions of AuNPs synthesized with thermal citrate methodology at varied C/G ratios generated with CellProfiler results

**REVERSE CITRATE METHOD**

When the colloid is heated to 100°C, trisodium citrate can act as a reducing agent in addition to a capping agent and theoretically should lead to the fabrication of smaller gold nanoparticle sizes at equivalent citrate:gold molar ratios used in the thermal citrate method. The reverse citrate method was modified by heating up solutions of trisodium citrate dihydride in DIW at varied concentrations to 100°C and subsequently adding room temperature solutions of HAuCl₄ in 5 ml DIW, allowing the solution to stir at 100°C for 15 minutes. The concentration of gold in solution was fixed at 0.001M and the citrate concentration was varied at the following citrate:gold molar ratios: 15, 10, 7.5, 5, 2.5. In this portion of the experimentation, a citrate:gold ratio of 1 was omitted based on the high polydispersity found when that ratio was
Table 7.2: Sizes of AuNPs synthesized with reverse thermal citrate method

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</table>

used in the thermal citrate method, discussed previously.

The behavior of the nanoparticles synthesized with the reverse citrate method were not entirely as expected. A significant finding was that particles synthesized using the reverse citrate method were not any smaller than those synthesized with the normal thermal citrate method at the same citrate:gold molar ratio. For example, at a C/G ratio of 10 the thermal citrate method yielded 14.5±1.9 nm particles and the reverse citrate method yielded 17.3±2.2 nm particles showing that the two methods were nearly within error of each other. Additionally, no meaningful trend was found when the citrate:gold ratio was changed between 15,10,7.5, and 5 in the reverse citrate method where the expectation would be that size would increase as the citrate:gold ratio decreased. A significant increase in size, of about 10 nm, was only observed when the C/G ratio was lowered to 2.5.

Figure 7.5 shows the TEM images of the gold nanoparticles synthesized under thermal citrate conditions with varying citrate:gold molar ratios. Size distributions generated from the average and standard deviation of particle sizes measured with CellProfiler are shown in Figure 7.6. Tabulated results of particle size analysis for each experimental point carried out both manually and with CellProfiler are listed in Table 7.2.
At room temperature the role of citrate in the AuNP synthesis is to act as a protective agent toward Oswald Ripening of the Au particles, controlling the ultimate size and dispersion of the colloid. As it was desired to change the room temperature NaBH$_4$ assisted AuNP synthesis method to produce larger AuNPs, modifications were made by changing both the HAuCl$_4$ concentration from 0.1–0.2 M and the C/G molar ratio from 1.5–4.5 independently. Figure 7.7 shows the TEM images of the gold nanoparticles synthesized with this methodology. Size distributions generated from the average and standard deviation of particle sizes measured with CellProfiler are shown in Figure 7.8. Tabulated results of particle size analysis for each experimental point carried out both manually and with CellProfiler are listed in Table 7.3. Particle sizing was only carried out for samples synthesized using 0.1M HAuCl$_4$ due to the irregular sizing and morphology of the nanoparticles synthesized at higher HAuCl$_4$ concentrations.
Using this methodology, undesirable characteristics were found when the HAuCl$_4$ concentration was increased to levels greater than 0.1M as shown in Figure 7.7, where the use of 0.15M HAuCl$_4$ resulted a bimodal size and shape distribution of small monodisperse spheres and large (>50 nm) cubes and the use of 0.2M HAuCl$_4$ resulted in irregular morphologies with obvious particle aggregation. This finding suggests that the room temperature NaBH$_4$ assisted AuNP synthesis method exhibits similar behavior to that observed in the literature data for the thermal citrate method, where increased HAuCl$_4$ concentration requires increased C/G ratios or possibly NaBH$_4$ to compensate for the increased ionic strength of the solutions. When 0.1M HAuCl$_4$ was used the AuNPs were consistently quasi-spherical and relatively monodisperse,
however, an interesting relationship was found with respect to the C/G molar ratio where AuNP diameter was decreased by increasing the C/G ratio from 1.5 to 3 but increased by increasing the C/G ratio from 3 to 4.5. Examination of Figure 7.8 and Table 7.3 shows that the average AuNP sizes for C/G ratios of 3 and 4.5 (at 0.1M HAuCl₄) are nearly within error of one another. As such, it’s possible that the further increase of C/G ratio from 3 to 4.5 simply offers a diminishing return on decreased particle size which would partially explain the unexpected relationship between C/G ratio and particle size observed for these points.

7.2 RAFT POLYMERIZATION

7.2.1 SYNTHESIS OF RAFT AGENT

The details of the synthesis of the RAFT agent, methyl-2-(butylthiocarbonothioylthio) propanoate, adapted from Liang et al [156], are described in the experimental section.
Figure 7.8: Size distributions of AuNPs synthesized with citrate and NaBH₄ at room temperature generated with CellProfiler results.

Table 7.3: Sizes of AuNPs synthesized with citrate and NaBH₄ at room temperature

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>0.1</td>
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<td>10.3±3.8</td>
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<td>9.93±1.7</td>
</tr>
<tr>
<td>0.1</td>
<td>3</td>
<td>3.8±0.9</td>
<td>3.8±0.9</td>
<td>3.77±0.5</td>
</tr>
<tr>
<td>0.1</td>
<td>4.5</td>
<td>6.8±2.1</td>
<td>6.8±2.1</td>
<td>7.07±1.7</td>
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<tr>
<td>0.2</td>
<td>4.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.15</td>
<td>4.5</td>
<td>*Didn’t analyze</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
After isolation of the desired product with column chromatography the chemistry of the RAFT agent was confirmed using 1H-NMR (solvent: CDCl$_3$) as shown in Figure 7.9. The following peaks were found, confirming the desired molecule: CH$_3$ δ 0.93 (triplet, 3H), CH$_2$ δ 1.43 (multiplet, 2H), CH$_3$ δ 1.59 (doublet, 3H), CH$_2$ δ 1.68 (quintet, 2H), CH$_2$ δ 3.36 (triplet, 2H), CH$_3$ δ 3.73 (singlet, 3H), CH δ 4.83 (quad, 1H)

7.2.2 Polymer length control

The molecular weight of the ptBA prepared using RAFT polymerization was tuned by adjusting the molar ratio between TBA monomer and the RAFT chain transfer agent, henceforth referred to as the TBA/CTA ratio. Since each polymer chain in-
Table 7.4: Properties of ptBA samples prepared with RAFT polymerization at varied tBA/CTA ratios

<table>
<thead>
<tr>
<th>Sample Key</th>
<th>TBA/CTA</th>
<th>Mn</th>
<th>PDI</th>
<th>N</th>
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<tbody>
<tr>
<td>ptba14a2</td>
<td>16.7</td>
<td>1711</td>
<td>1.06</td>
<td>11.4</td>
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<tr>
<td>ptba5g1</td>
<td>39.4</td>
<td>4834</td>
<td>1.15</td>
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</tr>
<tr>
<td>ptba87a1</td>
<td>97.5</td>
<td>9283</td>
<td>1.11</td>
<td>70.6</td>
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<tr>
<td>ptba87a2</td>
<td>127.1</td>
<td>14673</td>
<td>1.05</td>
<td>112.7</td>
</tr>
<tr>
<td>ptba87a3</td>
<td>155.5</td>
<td>15663</td>
<td>1.05</td>
<td>120.4</td>
</tr>
<tr>
<td>ptba160a1</td>
<td>178.8</td>
<td>24533</td>
<td>1.15</td>
<td>189.7</td>
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<td>ptba87a4</td>
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</tr>
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<tr>
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<td>390.6</td>
<td>51061</td>
<td>1.15</td>
<td>396.9</td>
</tr>
</tbody>
</table>

cludes one RAFT chain transfer agent molecule, the TBA/CTA molar ratio should, in theory, exactly equal the number of repeat units in each polymer chain. The measured molecular weights (Mn), polydispersion indices (PDI), and calculated number of repeat units (N) for each ptBA sample synthesized at TBA/CTA ratios is compiled in Table 7.4. The relationship between TBA/CTA ratio and the number of tBA repeat units (N) is plotted against the theoretical maximum in Figure 7.10.

7.2.3 Acid Hydrolysis of ptBA

Selected ptBA samples prepared via RAFT polymerization were converted in polyacrylic acid (PAA) via acid hydrolysis prior to AuNP functionalization using methodology adapted from Wu et al [171], discussed in detail in the experimental section. The penultimate step in the acid hydrolysis involves the dissolution of the solid into ether. Because PAA, and not ptBA, is soluble in ether this both serves to purify the polymer, allowing any unconverted ptBA to be discarded, and confirm its identity.

That being said, both $^1$H-NMR and ex-situ FTIR were used before and after the hydrolysis to confirm both the success of the RAFT polymerization to form ptBA and the acid hydrolysis of the t-butyl groups to form carboxylic groups. This data is shown in Figures 7.11 and 7.12 for the representative sample (5.98±0.18 nm AuNPs, 35.8 repeat unit PAA).
Examination of the $^1$H-NMR spectrum for ptBA (red) shows major peaks confirmative of the desired ptBA polymer: CH$_3$ δ 1.44 (singlets, 3H), CH$_2$ δ 1.82 (triplet, 2H), CH δ 2.24 (triplet, 1H), as well as peaks originating from the RAFT chain transfer agent end group carbons, as previously discussed. After hydrolysis, the PAA structure can be confirmed by the disappearance of these peaks and shifting due to slightly different chemical environment of the remaining proton groups.

Ex-situ FTIR measurements also proved useful in confirming the tert-butyl cleavage from the polymers. Figure 7.12 shows the disappearance of the (CH$_3$)$_t$-butyl asymmetric stretch around 2800 cm$^{-1}$ and appearance of the OH$_{PAA}$ stretch around 3300 cm$^{-1}$ following hydrolysis, while the $\nu$(C=O) peak, which should be present in both polymers, is preserved.
7.2.4 Characterization of PAA-AuNPs

Due to the large number of unique PAA-AuNP samples prepared, which varied in their AuNP diameters and PAA chain lengths, and the large experimental expense of doing exhaustive characterization on every sample, full characterization was performed only on a single PAA-AuNP sample which consisted of 5.98 AuNPs and PAA with 35.8 repeat units. Additional tests confirming polymer chemistry (1H-NMR, FTIR) before and after conversion from ptBA to PAA, hydrodynamic radius before and after grafting PAA to the AuNP surface (DLS), AuNP crystalline structure (XRD, HRTEM), and the grafting density of PAA on the AuNPs (TGA) were carried out for the representative sample only (5.98±0.18 nm AuNPs, 35.8 repeat unit PAA).
AuNP Crystal Structure

XRD and HRTEM studies were used to confirm that fcc metallic gold was synthesized. The X-ray Diffraction (XRD) pattern of the selected sample (5.98±0.18 nm AuNPs, 35.8 repeat unit PAA) is shown in Figure 7.13. To make the measurement, 1 mg of the selected sample (5.98±0.18 nm AuNPs, 35.8 repeat unit PAA) was washed 4x after functionalization and dried before scanning in the X-ray diffractometer at a rate of 1°/min from 30-80°2θ.

The pattern can be indexed to match fcc Au (PDF#04-0784). The crystallite size was found to be exactly 4 nm when Scherrer’s equation was applied to the broadening of the (111) peak. In this case, the difference between the TEM average particle size and XRD average crystallite size is not terribly concerning as XRD is
Figure 7.13: XRD Pattern of PAA-AuNPs (5.98±0.18 nm AuNPs, 35.8 repeat unit PAA) showing fcc Au structure with a 4 nm crystallite size measuring the average size of each coherently diffracting crystalline domain in the sample. Furthermore, XRD is a true bulk measurement while TEM will always be limited by the sample size of the particles counted. The fcc Au crystal structure can also be confirmed by the HRTEM image in Figure 7.14 where the visible lattice can be indexed to 0.23 nm. This value is equal to the expected d-spacing of the fcc Au (111) plane.

**Determination of Hydrodynamic Diameter**

A determination of hydrodynamic radius was made before and after functionalization of the selected 5.98±0.18 nm AuNPs with 35.8 repeat unit PAA. Adjustments to the
concentration of each sample was changed according to the procedure outlined in the experimental section and average hydrodynamic diameter was calculated by averaging the size distributions for those concentrations in which the result changed the least. This is shown in both cases in Figure 7.15, where the citrate capped AuNPs were found to have a hydrodynamic diameter of 4.92 nm and the PAA capped AuNPs were found to have a hydrodynamic diameter of 8.16 nm.

Determination of Grafting Density

The determination of polymer grafting density on a nanoparticle surface with TGA is a fairly straightforward procedure. In fact, the most serious difficulty encountered with making this measurement was the isolation of dry PAA-AuNPs via precipitation from solution without nanoparticle aggregation. To enable this precipitation, very large amounts of functionalized nanoparticles needed to be prepared, washed and concentrated with ultracentrifugation. Thus, because of the high experimental cost
Figure 7.15: DLS determination of hydrodynamic diameter of 5.98±0.18 nm AuNPs a) as synthesized/citrate capped and b) capped with 35.8 repeat unit PAA

and time of this measurement, the measurement of grafting density was only performed for one PAA-AuNP sample (PAA chains with 35.8 repeat units (N) grafted to 5.98±0.18 nm AuNPs).

A TGA-50 Shimadzu Thermogravimetric Analyzer equipped with a TGA-50H detector was used to make the measurement. After taring the weighing boat and balance, 0.716 mg of PAA-AuNPs were added. The sample was then heated to 80°C under an Ar atmosphere at a rate of 15°C/min and held for 30 minutes to allow for stabilization and removal of high volatility organic residues. Subsequently, the sample was heated at 10°C/min from 80-800°C, allowing a large enough window for the thermal decomposition of the grafted PAA. The resultant TGA profile is shown in Figure 7.16. No smoothing or manipulation was performed on the raw data presented and analysis was carried out by simply calculating the total mass loss of the sample and using this value to determine that the composition of the PAA-AuNPs (35.8N, 5.98±0.18 nm) was 11.76% PAA and 88.24% Au.

Using the information obtained from the AuNP TEM studies and polymer length analysis, it’s possible to calculate the mass of PAA on the particle and the grafting density in terms of PAA chains/particle and PAA chains/nm². First, the surface area (SA) and volume (V) of an AuNP can be found using the particle diameter (D_{TEM})
measured with TEM. Using these values together with the density of Au metal ($\rho_{\text{Au}}$) is 19.32 g/cm$^3$, which is based on the molar mass of the metal and the fcc unit cell packing density the Au particle mass ($m_{\text{Au}}$) can be calculated. Subsequently, the mass of the Au particle can be used to estimate the mass of PAA on the particle based on the composition measured with TGA. Finally, given the mass of PAA on the particle and the molecular weight of the PAA brush measured with TGA it is possible to quantify the number of PAA chains per particle, 65.3, and the number of PAA chains/nm$^2$, 0.58, both acceptable means of reporting grafting density. This grafting density is on the order of what others have seen when grafting thiolated ligands to gold surfaces [156, 187, 246], where measurements have reportedly ranged from 0.04-4.35 chains/nm$^2$. 

Figure 7.16: TGA profile of PAA-AuNPs
Table 7.5: CCD standard orders and experimentally measured values for the determination of the effect of AuNP size and PAA polymer size on $A\beta$ aggregation

<table>
<thead>
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<th>Experimental Points</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td>$N$</td>
<td>$D$ (nm)</td>
</tr>
<tr>
<td>1</td>
<td>Factorial</td>
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<td>9.2</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>112</td>
<td>9.2</td>
</tr>
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<td>36</td>
<td>19.8</td>
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<tr>
<td>4</td>
<td></td>
<td>112</td>
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<tr>
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</tr>
<tr>
<td>9</td>
<td>Center</td>
<td>74</td>
<td>14.5</td>
</tr>
</tbody>
</table>

7.3 Selected PAA-AuNP Samples for $A\beta$ Aggregation Experiments

A central composite design of two variables (AuNP diameter and PAA degree of polymerization) was populated using selected PAA-AuNP samples of varying physical properties as previously described. Since the design was cast with variables which could not be discretely controlled, we relaxed our exact design levels (ie. center point, corner points, and $\alpha$ level which fixes the location of axial points) such that error between the design points and their true, experimentally measured values was minimized. Figure 7.17 shows both the optimized design points and the experimental averages and error bars to indicate standard deviation. This information is also listed in Table 7.5 alongside the standard order of each design point. The TEM images and size distributions corresponding to the CCD design points listed in Table 7.5 are shown in Figures 7.18 and 7.19, respectively.

7.4 $A\beta$ Aggregation Experiments

Prior to aggregation tests the PAA-AuNP samples listed in Table 7.5 were washed repetitively with water and ultracentrifuged to produce concentrated samples in DIW without excess citrate or PAA in solution. Subsequently, precise determinations of
Figure 7.17: CCD layout for the determination of the effect of AuNP size and PAA polymer size on Aβ aggregation. Experimentally measured points are shown in gray with error bars indicating standard deviation of AuNP diameter and PDI of the PAA degree of polymerization, design points are shown as red circles.

PAA-AuNP concentrations were made using UV-Vis and Beer’s Law, the methodology of which is discussed in the experimental section of this thesis.

Experiments to measure the lag extension factor (LEF) associated with Aβ aggregation both with and without the inclusion of 100 mM NaCl were performed by Nicholas van der Munnik. The details of the experimentation were as follows: 60 wells of a 96-well microplate layout were loaded with 10μM Aβ, 40mM tris (pH 8.0), 20μM Thioflavin T (ThT) and either 0 or 100mM NaCl. The 36 wells on the perimeter of the microplate were left empty to avoid anomalous readings. For both the salt and no salt cases wells were loaded with samples 1-9 of the CCD listed in Table 7.5 at a concentration of 1 nM. The remaining wells were left empty of PAA-AuNP samples.
Figure 7.18: TEM images of selected AuNPs for central composite design

Figure 7.19: Size distributions generated with CellProfiler of selected AuNPs for Aβ aggregation experiments
Figure 7.20: Example of the fluorescence indicated lag time of Aβ from a typical microplate layout experiment

and were used as controls. The 10 unique samples with 0 mM NaCl and 10 unique samples with 100 mM NaCl comprised 20 samples which were repeated 3 times within each experiment.

During the experiment, Aβ aggregation was quantified by the fluorescence of ThT which occurs when the molecular rotor binds to the β-sheets which are formed as Aβ aggregation commences. Aβ monomer was purified with size exclusion chromatography (SEC) prior to aggregation experiments. Fluorescence measurements were taken at 15 minute intervals using a Biotek Synergy 2 Microplate Reader. An example of how the lag time was determined from fluorescence data for each sample and standard is shown in Figure 7.20, where the quantitative analysis of the lag curves was carried out using an algorithm developed by Nicholas van der Munnik. Lag extension factor is defined as the ratio between the lag time measured for each PAA-AuNP treated sample and the lag time of the control for the same salt concentration measured on the same microplate layout.
Figure 7.21: Lag extension factor for Aβ aggregation for CCD samples both with (red dotted bars) and without 150 mM NaCl (blue plain bars). All data was obtained at a pH of 8.0. The author would like to acknowledge Nicholas van der Munnik for performing the aggregation experiments.

For a given NP sample in a given experiment, the LEF values used in the analysis of data were an average of four repeat measurements within the same plate layout experiment. In total, each experiment including four replicates of each sample was repeated over five distinct Aβ aggregation assays. The average lag extension factor and standard deviation based on the measurements from the totality of microplate layout experiments for each sample in the CCD for both the 0 mM NaCl and 100 mM NaCl are shown in Figure 7.21 where error bars represent the standard error of the mean.

Visual examination of the lag extension data for all CCD samples and for both conditions shows that sample 7 was the strongest inhibitor and sample 8 was the weakest. These standards orders belong to the smallest and largest AuNP diameters investigated, respectively. In general, more variation in response was observed for the 0 mM NaCl case when compared to the 150 mM NaCl case and the best performing
samples (7, 2, and 9) had higher LEFs in the absence of NaCl. In fact, the only sample which had a greater LEF in the presence of NaCl was sample 3, which appears to promote aggregation at low ion concentrations and inhibit aggregation at high ion concentrations when compared to the mean LEF.

With that said, the observations which can be made by visually comparing the lag extension factors of the CCD samples in Figure 7.21 do not tell the full story of the data. To make an informed, statistically relevant analysis of the data which properly accounts for the full range and combinations of variables investigated it is necessary to complete the iterative process of model fitting and Analysis of Variance (ANOVA) which provides the effect and significance of each variable and model term.

Let us call the AuNP diameter, D, and the PAA degree of polymerization, N, for simplicity. A fully fitted CCD regression model could potentially include all linear and quadratic terms comprised of these two variables: D, N, D\(^2\), N\(^2\), and ND. This full quadratic model was the starting point of the CCD analysis. In both cases, the final models were established to only include those terms which passed an F-test with a p-value < 0.05 as well as any terms which were necessary to maintain model hierarchy (i.e. in order to include the term ND we must also include the term N and the term D). Additionally, the residuals of the fitted models were checked for normality and for any time or run order dependencies which ensures the validity of the F-test evaluation.

In the 100 mM NaCl case implementing the considerations discussed above led to the conclusion that the only statistically significant term necessary to predict the lag extension factor was the AuNP diameter (D) which had an inversely proportional effect on lag. On average, increasing the AuNP diameter from 5.8 to 23.2 nm (when averaged over all relevant PAA polymer lengths) had the effect of decreasing the lag extension factor from roughly 1.20 to 0.90. The model R-squared value was calculated to be 34.60%. The resultant contour plot which can be generated using the statistical
model for the 100 mM salt case is shown in Figure 7.22 where the complete lack of curvature is a result of the absence of any quadratic or two-factor terms in the model.

Similar to the 100 mM NaCl case, the AuNP diameter (D) was found to be the most significant term for the 0 mM NaCl case, affording the largest effect on lag extension factor. On average, increasing the AuNP diameter from 5.8 to 23.2 nm had the effect of decreasing the lag extension factor from roughly 1.3 to 0.9. Unlike the 150 mM NaCl case, the 0 mM NaCl case also revealed a significant effect with respect to both the degree of polymerization (N) and the square of that term (N^2). Specifically, the lag extension factor was found to increase with increasing polymer length until reaching a maximum at 93.5 and decreasing for N>90. The R-squared value for the model was calculated to be 67.03%. The contour plot which can be generated using the statistical model for the 0 mM salt case is shown in Figure 7.23 which highlights the unique dependence of the lag extension factor on the square of
the degree of polymerization ($N^2$).

Overall, the effects of the PAA-AuNPs on LEF, being achieved at stoichiometric ratios of NP to $A\beta$ of 1:10,000, are extremely potent when compared with other $A\beta$ aggregation inhibition molecules. Of particular interest was the exceptional LEF of sample 7 which was comprised of very small PAA-AuNPs with a core diameter of 5.8 nm and a degree of polymerization of 74, which was an intermediate value in the design. Sample 7 inhibited aggregation in both the low and high ion cases, with an average LEF of 1.44 and 1.35, respectively. The strong inhibitor effect of this PAA-AuNP material, together with the variability observed across the CCD, confirm the ability to tune lag extending behavior by adjusting the PAA-AuNP architecture.

As previously mentioned, the inhibitory effects observed in the case of 0 mM NaCl were screened in the 150 mM NaCl case and, as an overall trend, the variability of the response was muted. The measurement of increased LEF for 0mM NaCl is
not entirely surprising, as $\alpha\beta$ to aggregate more quickly at higher ion concentrations [247], and reflect the microscopic phenomenon of altered electrostatic screening. Even with the small amount of electrostatic screening which inevitably exists even in the 0 mM NaCl case, due to the ability of hydronium and hydroxide ions and the tris molecule to accrue charge, the different ionic strengths of the two cases were found to significantly effect $\alpha\beta$ to aggregation behavior.

Comparing the statistically significant effects in both the 0 mM and 150 mM NaCl cases indicated by the contour plots in Figures 7.23 and 7.22, respectively, and discussed previously it is interesting to note that the LEF was increased significantly in both cases by decreasing the AuNP diameter ($D$). Intuitively, one might expect this to result from the differences in diffusitivities between the smaller and larger AuNPs (5.8-23.2 nm). Additionally, a curvature effect exists in which PAA chains tethered to a 5.8 nm diameter AuNP surface are in a comparably much different environment than those tethered to a 23.2 nm diameter AuNP surface due to their very different radii of curvature. To illustrate this, consider that PAA chains of identical grafting density and length would be much more crowded near the surface of a larger diameter AuNP particle. This effect would lead to unique molecular organization of identical PAA chains on differently sized nanoparticles which could lead to varied solution effects and interactions with $\alpha\beta$.

An interesting finding was the dependence of LEF in the 0 mM NaCl case on both $N$ and $N^2$, where LEF is maximized close to $N$=93. As previously mentioned, the emergence of this effect only in the case of low ion concentration is likely a result of the lowered electrostatic screening. Furthermore, that the effect of polymer length was muted in the 150 mM NaCl case while AuNP diameter was not is unsurprising due to the ability of the PAA chains to accrue charge. The differences in the ensemble average shape of the end-tethered PAA chains are likely to be far more significant, in terms of the affected solution space, than any structural which might be observed if
the AuNP surface accrued charge. Furthermore, the existence of an optimum polymer length for a particular AuNP size was not unexpected based on previous experimental work.

As a final note, in both the 0 mM NaCl and 100 mM NaCl cases no significant interaction between the two model terms, AuNP diameter (D) and PAA degree of polymerization (N) were found. It is possible that the effective hydrodynamic radius of each PAA-AuNP sample, rather than an interaction between the two components, is the most effective predictor of LEF. That being said, the levels chosen for each parameter ultimately determine the statistical significance of the ND interaction, as one would expect an interaction effect to be inevitable if extreme levels of each parameter were selected where the physically properties of the material would be entirely different.

In a previous study, AuNPs with 8 and 18 nm diameters functionalized with electrostatically associated layers were found to completely inhibit Aβ aggregation when a 40 µM solution of Aβ was tested with 20-200 pM of AuNPs [121]. While this presents is a significantly stronger inhibitory effect than what was measured in this work, direct quantitative comparison between the two studies in terms of potency and LEF is fruitless due to the very important and uncontrolled variables used in each study (i.e. Aβ supplier and method of surface functionalization). Certain trends, however, can provide useful insights.

7.5 Conclusions

The presented work provides a comprehensive review on the existing knowledge regarding size controlled synthesis of quasi-spherical gold nanoparticles. Specifically, this work validated and leveraged existing reported synthesis methodology using design of experiments to establish predictive models for the synthesis of AuNPs of particular diameters. In addition, targeted one-factor-at-a-time (OFAT) experiments
were completed in specific areas of the design space to achieve AuNP colloids with precisely the desired size distributions. Polyacrylic acid polymers of varied lengths were prepared by tuning the ratio between monomer and chain transfer agent used in the synthesis. Ultimately, PAA-AuNP hybrids with varied NP diameters and polymer lengths were prepared and characterized using TEM, GPC, TGA, $^1H$-NMR, DLS, and UV-Vis. These samples were then tested using a central composite experimental design to resolve the effect of the aforementioned nanomaterial properties on the lag extension factor (LEF) measured during Aβ aggregation experiments.

Overall, it was found that the effects of the PAA-AuNPs on LEF, being achieved at stoichiometric ratios of NP to Aβ of 1:10,000, are extremely potent when compared with other Aβ aggregation inhibition molecules and that the ability of the PAA-AuNP hybrids to disrupt the aggregation process was sensitive to their architecture as demonstrated by the results of the CCD analysis. In particular, the LEF was increased significantly when the AuNP diameter was decreased in both the 0 mM and 150 mM NaCl cases, which could be owed to curvature effects or the higher diffusitivities of the smaller particles. Also of interest was the finding that the variability in the response was muted in the 150 mM NaCl case when compared to 0 mM NaCl. In particular, the degree of polymerization (N) and $N^2$ emerged as significant factors only when 0 mM NaCl was used and the predictive model suggests that under these conditions, LEF is maximized when N=93. The emergence of these statistically significant factors only in the case of low ion concentration is likely a result of the lowered electrostatic screening in solution. Finally, the absense of significant interaction terms between the two factors investigated, AuNP diameter and polymer length, suggest that the hydrodynamic radius of the hybrids may be the determining factor on LEF for the design levels and conditions studied.
Chapter 8

Conclusions and Outlook

This body of work explored several applications focused on the use of high-throughput experimentation and design of experiments to uncover relationships between preparation factors, structural properties, and functionality of nanomaterials. Three examples in oxidation catalysis were investigated, including cobalt oxide catalyzed CO oxidation, Cu-Ag/α-Al₂O₃ catalyzed ethylene epoxidation, and doped Mo₈V₂Nb₁ catalyzed ethane partial oxidation. In addition, functional PAA-AuNP nanomaterials were developed and studied for their efficacy as potential Alzheimer’s therapeutics.

An important commonality between each of these topics is the high sensitivity of nanomaterial properties and functionality to the way the nanomaterials are prepared. A similar workflow was adopted in each material development application which involved an in depth survey of literature and existing hypothesized synthesis-structure and structure-activity relationships to establish the relevant parameter space in terms of materials preparation. Subsequently, the parameter space was screened using iterative design of experiments in a systematic manner which facilitated materials optimization whilst providing conclusive information on which preparation variables and structural properties were most important in terms of materials performance when directly compared.

The usefulness of this type of approach is evident when considering the results of the investigation of cobalt oxide CO oxidation catalyst preparation discussed in Chapter 3 of this thesis. This work involved the use of iterative design of experiments to screen six parameters relevant to the one-pot colloidal synthesis of CoOx
on nanoparticles and establish their effects on nanomaterial properties such as phase, size, and structure as well as their CO oxidation activity. Of the six variables studied, it was found that the concentration of CoAc used in the synthesis together with the synthesis aging temperature had the most significant impact on nanoparticle structure and catalyst activity with light off temperatures below 90°C occurring above 0.06 M CoAc and below 250°C.

Experimentation revealed that the variations in CO oxidation light off temperatures could largely be explained by changes in catalyst structure pre-calcination. In part, activity variations coincided with f-CoO particles with high degrees of grain boundary consolidation, δILJC, formed at intermediate aging temperatures and CoAc concentrations which could enhance activity by providing active sites in close proximity to grain boundaries with fast oxygen diffusion from the bulk. Activity variations also coincided with the formation of h-CoO particles which exhibited preferential growth along the c-axis. The latter tended to form at low ramp rates, low aging temperatures, and high CoAc concentrations and were shown with HRTEM studies to oxidize into Co₃O₄ with highly active (110) surface facets and Co³⁺ enrichment. These findings demonstrate that Co³⁺ and grain boundary enrichment are the most significant structural variables in a design space assessing multiple properties and provide a novel approach in the control of these properties. Additionally, as previously stated, the synthesis variables and structural properties which were found to be only weakly correlated with CO oxidation activity are also important and useful results. For example, particle size is a topic which receives a great deal of attention throughout heterogeneous catalytic applications and it is noteworthy here that the formation of grain boundaries was a comparably much more important structural property. As a final thought, it was curious that the formation of catalytically active grain boundaries and the surface enrichment of Co³⁺ were mutually exclusive properties across the parameter space screened. Further investigation into preparation
conditions which may yield catalysts which exhibit both structural properties could be both scientifically interesting and topical.

Chapter 4 of this thesis discussed the preparation of Cu-Ag/α-Al_2O_3 catalysts for use in a slightly more complex oxidation reaction; the selective epoxidation of ethylene into ethylene oxide. In this work, high-throughput experimentation and parallel 2^2 factorial screening designs were used to survey the parameter space with respect to operating conditions and co-promoter type, loading, and impregnation sequence of co-promoters. One of the key objectives in this work was to determine the Cu loadings and operating conditions for which Cu was able to promote the epoxidation relative to plain Ag, where the greater body of work suggested a number of competing explanations and findings with regard to these variables and the phase of the Cu in the catalyst. The results presented in this thesis suggest that the ideal loading of Cu on a 15% Ag/α-Al_2O_3 catalyst under reaction conditions of 10% ethylene + 10% oxygen (C_2H_4/O_2=1) at 1 atm is 0.2% by weight, where the catalyst would likely be comprised of Ag nanoparticles with Cu_x oxide phase segrated on the Ag surface. At this loading, under these conditions, this phase segregated Cu_x oxide provides a promotional effect and increases the epoxide selectivity. Further increases in the Cu loading above 0.2%Cu were found to be detrimental for epoxide selectivity under standard reaction conditions. That said, for high ethylene feed fractions (C_2H_4/O_2=5) a 1%Cu containing catalyst was found to increase selectivity dramatically. XPS and kinetic evaluation of the 1%Cu-Ag catalyst suggest that this effect is the result of a surface alloy formation under these conditions which makes the oxygen dissocation step much more efficient. An important conclusion of this portion of the work is that there is an interaction between the Cu loading and the reaction feed conditions which changes the oxidation state of the Cu species and the structure of the Cu-Ag catalyst, thus changing the ability of Cu to promote the formation of ethylene oxide. This finding is quite useful in the greater landscape of the field as it
can help explain certain discrepancies between results reported for Cu containing Ag catalysts in the literature.

In addition, Chapter 4 discusses a wide scale co-promoter screening was completed where both conventional and non-conventional epoxidation promoting elements were investigated. The most promising candidates from the screening were found to be Au, Re, Sn, and Cs, which were each optimized in terms of their impregnation sequence and loading. It was found that these variables did not have a statistically significant effect on the morphology or activity of Re and Au containing catalysts, while differences in Sn and Cs containing materials were notable. Specifically, it was found that increased Cs loading and co-impregnation with Ag greatly improved the dispersion of Ag on the α-Al₂O₃ support. In the case of Sn, it was found that lower Sn loadings benefited EO selectivity while impregnation order made little difference. In addition, it was found that the 0.2%Cu-15%Ag at all Sn loadings and impregnation sequences investigated displayed peculiar porous agglomerates thought to arise due to effects of Sn on the mobility of Cu and Ag. A fully promoted (Cu-Au)-Re-(Sn-Cs-Ag)/α-Al₂O₃ catalyst was synthesized using the optimal impregnation sequence and loading for each co-promoter which had a measured EO selectivity of roughly 69% at 5% ethylene conversion which is more than double that of the Ag only catalyst evaluated at comparable conditions. An interesting caveat was that the same catalyst was 30% less selective toward EO when Cu was omitted from the formulation altogether. Further work elucidating the effect of Cu on the morphology, surface structure and kinetic behavior of the Au-Re-(Sn-Cs-Ag)/α-Al₂O₃ would be useful in determining the origin of this disparity. Additionally, as a trend it was found that Cu loading had a profound effect on the morphology of Ag nanoparticles both with and without co-promoters and further investigation of this relationship, particularly in catalysts which also contain Cs and/or Sn could be very interesting.

Chapter 7 of this thesis discussed studies focusing on optimizing the doping of
acid and redox elements into Mo$_8$V$_2$Nb$_1$ mixed metal oxide ethane partial oxidation catalysts. Specifically, DOE methodology was implemented to gain insights on the impact of tuning the balance between the acidity and redox behavior of the catalyst via the addition of the selected dopants and to identify useful trends to aid the design of mixed metal oxide EPO catalysts in the future. Analysis was carried out to correlate the redox element loading (Pd or Ni or Ti) and acid element loading (K or Cs or Te) with the catalytic performance (eg. product distribution) and structural integrity (eg. grain size, structure, elemental uptakes) of the materials. It was found that across all catalyst compositions explored, an excess of surface acidity relative to the redox element (R/A ratio of 0.005) benefited both ethylene and acetic acid formation. Additionally, investigation of the total dopant level (D/H ratio) led to the finding that doping high levels of Ti optimized the selectivity for both AA and ethylene, while doping high levels of Ni and Pd led to the formation of combustion products. Overall, AA production was favored with TiTe doping while ethylene production was favored with NiTe doping. Additionally, it was found that Cs doped catalysts ubiquitously favored ethane combustion. The effects of dopant composition on the catalyst structure were elucidated, where the extent of phase segregation and incorporation of dopants into the base catalyst was most sensitive to the acid/base element doped, and the incorporation of cesium was found to trigger the formation of multiple secondary phases. Overall, tuning the balance between redox and acid elements doped into Mo$_8$V$_2$Nb$_1$ catalysts resulted in not only changes to the surface acidity and redox properties, but also induced a change in the bulk catalyst structure, the coupled effects of which were found to ultimately determine the materials catalytic properties. An important conclusion of this work which is topical in the development of any partial oxidation catalyst was that both acid and redox functionality were important in the formation of both ethylene and acetic acid. Further work using temperature programmed and spectroscopic techniques focused on elucidating exactly
how the surface acidity and reducibility changes with dopant incorporation would be very useful in strengthening our understanding of the relationships between dopants, surface structure, and reaction mechanism.

Chapter 8 of this thesis discussed the development of functional PAA-AuNP materials with controlled polymer lengths and nanoparticle size distributions. Specifically, a comprehensive review on the existing knowledge regarding size controlled synthesis of quasi-spherical gold nanoparticles is presented and experiments were carried out with the goal of validating and leveraging this information such that AuNPs of particular diameters could be synthesized on demand. Polyacrylic acid polymers of varied lengths were prepared by tuning the ratio between monomer and chain transfer agent used in the synthesis. Ultimately, PAA-AuNP hybrids with varied NP diameters and polymer lengths were prepared and characterized using TEM, GPC, TGA, $^{1}H$-NMR, DLS, and UV-Vis. These samples were then tested using a central composite experimental design to resolve the effect of the aforementioned nanomaterial properties on the lag extension factor (LEF) measured during Aβ aggregation experiments. Overall, it was found that the effects of the PAA-AuNPs on LEF, being achieved at stoichiometric ratios of NP to Aβ of 1:10,000, are extremely potent when compared with other Aβ aggregation inhibition molecules and that the ability of the PAA-AuNP hybrids to disrupt the aggregation process was sensitive to their architecture as demonstrated by the results of the CCD analysis. In particular, the LEF was increased significantly when the AuNP diameter was decreased in both the 0 mM and 150 mM NaCl cases, which could be owed to curvature effects or the higher diffusivities of the smaller particles. Also of interest was the finding that the variability in the response was muted in the 150 mM NaCl case when compared to 0 mM NaCl. In particular, the degree of polymerization (N) and N² emerged as significant factors only when 0 mM NaCl was used and the predictive model suggests that under these conditions, LEF is maximized when N=93. The emergence of these
statistically significant factors only in the case of low ion concentration is likely a result of the lowered electrostatic screening in solution. Finally, the absence of significant interaction terms between the two factors investigated, AuNP diameter and polymer length, suggest that the hydrodynamic radius of the hybrids may be the determining factor on LEF for the design levels and conditions studied. In general, these findings could be strengthened and improved upon by completing further experiments which target how nanoparticles with different measured diffusivities or with different binding regimes of PAA affect the aggregation process. Additionally, while the parameter space with respect to AuNP size and polymer length appear to be optimized, an additional larger scale experiment could be useful in ruling out the possibility of a local optimum.

While the exact workflow followed in each application differed depending on the specifics of the materials development goals and existing knowledge, the overall objectives, to simultaneously optimize the materials preparation process while building an improved fundamental understanding of relevant synthesis-structure-activity relationships, were similar in each case. In fact, the overarching goal in each project discussed was to probe the greater body of work in a targeted manner to learn which variables and properties were comparably most important in optimizing materials performance in applications where an overwhelming number of possible preparation and structure-related explanations have been offered to explain trends in materials performance. As materials development moves forward in areas where ideas, methodology, and conclusions are often disparate and difficult to integrate with one another, studies such as those presented in this thesis, which focus on the connectivity within the larger body of work, will become increasingly necessary.
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