

UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

W.R. GRACE & CO.-CONN

Petitioner

v.

G.W. ARU, LLC ET AL.

Patent Owner

Patent 11,224,864

DECLARATION OF MICHAEL P. HAROLD, PH.D.

I, Michael P. Harold, declare as follows:

1. I attach my resume as Exhibit 1 to this declaration.

Experience and Qualifications

2. I am the Cullen Engineering Professor of Chemical and Biomolecular Engineering at the University of Houston. From May to August 2013, I was the Acting Dean of the Cullen College of Engineering, also at the University of Houston.

3. I received my B.S. in Chemical Engineering from Penn State in 1980 and earned my Ph.D in Chemical Engineering from the University of Houston in 1985.

4. I have been a Professor at the University of Houston since 2000. My research focuses on catalytic reaction engineering, including the catalytic reduction of NO_x to nitrogen in the oxidizing atmosphere of lean burn and diesel vehicles. I have authored at least 185 peer-reviewed papers.

5. In 2014, I was elected a Fellow of the American Institute of Chemical Engineers. In 2013, I received the Esther Farfel Award, which is the top honor to a university faculty member at the University of Houston. In 2019 I received the Award for Excellence in Applied Catalysis from the Southwest Catalysis Society, a regional chapter of the North American Catalysis Society.

6. I am the Founder and Principal Investigator of the Texas Center for Clean Engines, Emissions & Fuels (TXCEF), a UH Center involved in the

research, development, testing, and implementation of emission control technologies. TXCEF involves a partnership between UH, the City of Houston, the State of Texas, and third-party companies. Since 2003 the Center has had grants awarded totaling over \$20 million.

7. Between December 2011 and 2021, I served as the Editor-in-Chief of the *AIChE Journal*, the journal of the world's leading organization for chemical engineering professionals. Since 2010, I have been on the Editorial Board of *Reviews in Chemical Engineering* and from 2009 to 2011, I was a Consulting Editor of *Industrial & Engineering Chemistry Research*.

8. In 2004, I served as Editor of a special issue in *Catalysis Today* on "NO_x Reduction for Diesel and Lean Burn Engines."

9. Before joining the faculty of the University of Houston in 2000, I worked for the DuPont Company, ultimately becoming the Research Manager for Chemical Process Fundamentals. I also served as the Global Technology for Polymer & Fiber R&D. During my years at DuPont I was involved in the research and development of polymer intermediates manufacturing and chemical reaction engineering.

10. I have reviewed U.S. Patent No. 11,224,864 ("the '864 Patent") (WRG-1001), assigned to G.W. Aru, LLC. I have also reviewed at least the following patents and printed publications:

- Prosecution History of the '864 Patent (“the Prosecution History”) (WRG-1002);
- U.S. Patent Application 2007/0197379 to Miura (“Miura”) (WRG-1004);
- U.S. Patent No. 6,509,290 to Vaughn, et al. (“Vaughn 290”) (WRG-1005);
- U.S. Patent No. 6,358,881 to Peters, et al. (“Peters”) (WRG-1006);
- U.S. Patent Application 2005/0054516 to Vaughn, et al. (“Vaughn 516”) (WRG-1007);
- U.S. Patent No. 7,053,024 to Baker, et al. (“Baker”) (WRG-1008);
- Great Britain Patent No. 2,310,384 to Lin, et al. (“Lin”) (WRG-1009);
- Standard Test Method for Determination of Attrition of FCC Catalysts by Air Jet (D5757) (“ASTM Standard”) (WRG-1010);
- U.S. Patent No. 7,230,035 to Espinoza (“Espinoza”) (WRG-1011);
- I.V. Babich, K. Seshan, L. Lefferts, “Nature of nitrogen specie in coke and their role in NO_x formation during FCC catalyst regeneration,” *Appl. Catal. B. Environmental*, 59, 205-211 (2005) (“Babich”) (WRG-1012);
- Lang, W., P. Laing, Y. Cheng, C. Hubbard, and M.P. Harold, “Co-Oxidation of CO and Propylene on Pd/CeO₂-ZrO₂/Al₂O₃ Monolith Catalysts: A Light-off, Kinetics, and Mechanistic Study,” *Appl. Catal. B. Environ.*, 218, 430-442 (2017) (“Lang”) (WRG-1013);
- D. Wu, F. Wu, Z. Gu, “Catalyst Attrition in an ASTM Fluidized Bed,” *Catalysis Today*, 264 (2016) 70-74 (“Wu”) (WRG-1014);
- R. Cocco, Y. Arrington, R. Hays, J. Findlay, “Jet Cup Attrition Testing,” *Powder Tech.*, 200 (2010) 224-233 (“Cocco”) (WRG-1015);
- G.W. Aru Proposed Claim Construction Statement (WRG-1016).

11. Although for the sake of brevity this Declaration refers to selected portions of the cited references, it should be understood that one of ordinary skill in

the art would view the references cited herein in their entirety, and in combination with other references cited herein or cited within the references themselves. The references used in this Declaration, therefore, should be viewed as being incorporated herein in their entirety.

12. I am not, and never was, an employee of W.R. Grace & Co.-Conn. I have been engaged in the present matter to provide my independent analysis of the issues raised in the petition for *inter partes* review of the '864 patent. I received no compensation for this declaration beyond my normal hourly compensation based on my time actually spent studying the matter, and I will not receive any added compensation based on the outcome of this *inter partes* review of the '864 patent.

13. Based upon my experience in this area, a person of ordinary skill in the art of the '864 patent at the time of the invention ("POSITA") is a person who would have had an advanced degree in a relevant field, such as chemistry, chemical engineering, or material science, with experience working with supported metal catalysts, and would have had at least two to three years of experience with oxidation catalysts and their application. Additional work experience can compensate for less formal education, and vice versa.

14. Based on my experiences, I have a good understanding of the capabilities of a POSITA. Indeed, I have taught, participated in organizations, and worked closely with many such persons over the course of my career.

Overview of Conclusions Formed

15. This declaration explains the conclusions that I have formed based on my analysis. To summarize those conclusions, based upon my knowledge and experience and my review of the prior art publications described in this declaration, I believe that:

- Claims 1, 3, 6, 7, 12-19, 21 are obvious over Miura and Applicant Admitted Prior Art (“AAPA”)
- Claim 9 is obvious over Miura and AAPA and in further view of Vaughn 290
- Claims 10 and 11 are obvious over Miura and AAPA and in further view of Peters or, alternatively, Vaughn 516
- Claims 1-8, 12-22 are obvious over Miura and Baker
- Claim 9 is obvious over Miura and Baker and in further view of Vaughn 290
- Claims 10 and 11 are obvious over Miura and Baker and in further view of Peters or, alternatively, Vaughn 516
- Claims 1-8, 12-22 are obvious over Lin and Baker
- Claim 9 is obvious over Lin and Baker and in further view of Vaughn 290
- Claims 10 and 11 are obvious over Lin and Baker and in further view of Peters or, alternatively, Vaughn 516
- Claims 1-4, 6, 12-15, 18, 19, 21, 22 are obvious over Espinoza and AAPA

Interpretations of the ’864 Patent Claims at Issue

16. I understand that, for purposes of my analysis in this *inter partes* review proceeding, the terms appearing in the patent claims should be interpreted according to their “ordinary and customary meaning.” In that regard, I understand

that the best indicator of claim meaning is its usage in the context of the patent specification as understood by a POSITA. I further understand that the words of the claims should be given their plain meaning unless that meaning is inconsistent with the patent specification or the patent's history of examination before the Patent Office. I also understand that the words of the claims should be interpreted as they would have been interpreted by a POSITA at the time of the invention, *i.e.*, as of the effective filing date of the patent application. Accordingly, I have used the earliest listed priority date of the '864 patent, April 2, 2018, as the point in time for claim interpretation purposes.

Legal Principles

Obviousness

17. I have been informed that a patent claim is invalid as “obvious” under 35 U.S.C. § 103 in light of one or more prior art references if it would have been obvious to a POSITA, taking into account (1) the scope and content of the prior art, (2) the differences between the prior art and the claims, (3) the level of ordinary skill in the art, and (4) any so called “secondary considerations” of nonobviousness, which include: (i) “long felt need” for the claimed invention, (ii) commercial success attributable to the claimed invention, (iii) unexpected results of the claimed invention, and (iv) “copying” of the claimed invention by others. For purposes of my analysis above and because I know of no indication from the

patent owner or others to the contrary, I have applied the earliest listed priority date of the '864 patent, April 2, 2018, in my obviousness analyses, although in many cases the same analysis would hold true even at an earlier time than April 2, 2018.

18. I have been informed that a claim can be obvious in light of a single prior art reference or multiple prior art references. To be obvious in light of a single prior art reference or multiple prior art references, there must be a reason to modify the single prior art reference, or combine two or more references, in order to achieve the claimed invention. This reason may come from a teaching, suggestion, or motivation to combine, or may come from the reference or references themselves, the knowledge or “common sense” of one skilled in the art, or from the nature of the problem to be solved, and may be explicit or implicit from the prior art as a whole. I have been informed that the combination or modification of familiar elements according to known methods is likely to be obvious when it does no more than yield predictable results. I also understand it is improper to rely on hindsight in making the obviousness determination. *KSR Int’l Co. v. Teleflex Inc.*, 550 U.S. 398, 421 (2007).

Applicant Admitted Prior Art (AAPA)

19. I understand that admissions by an applicant in the specification and during prosecution constitute an admission which can be relied upon for both anticipation and obviousness determinations, regardless of whether the admitted

prior art would otherwise qualify as prior art under the statutory categories of 35 U.S.C. 102. I further understand that a patentee's admissions regarding the scope and content of the prior art under § 103 can be used, for example, to: (1) supply missing claim limitations that were generally known in the art prior to the invention or the effective filing date of the claimed invention; (2) support a motivation to combine a particular disclosure; or (3) demonstrate the knowledge of the ordinarily-skilled artisan at the time of the invention or the effective filing date of the claimed invention. I further understand that the applicant need not explicitly identify a disclosure as prior art for the admission to attach. Lastly, I understand that the specific statements made in the specification and during prosecution of the '864 patent relating to microspheres and average particle size constitute AAPA and may be relied upon in an obviousness determination.

State of the Art

20. CO to CO₂ combustion promoters, which are generally referred to as oxidation catalysts, are well known and are commonly used in a fluid catalytic cracking (FCC) unit. FCC is a process that converts heavy fractions of petroleum oil to lighter products, which are in greater demand. In FCC processes, fluidizable catalyst particles are contacted in a conversion zone of high temperatures with hydrocarbons such as to crack higher boiling hydrocarbons to lower boiling hydrocarbons. Common components of catalyst particles are an aluminosilicate

component and a porous inorganic oxide matrix. This type of catalyst must be regenerated to low carbon levels to assure that the catalyst particles possess desired activity and selectivity before the particles are recycled to the conversion or cracking zone.

21. The function of combustion promoters is to oxidize carbon monoxide to carbon dioxide (*i.e.*, convert CO to CO₂). High residual concentration of carbon monoxide in flue gases from regenerators has been a known problem. The oxidation of carbon monoxide is highly exothermic and can result in so-called “carbon monoxide afterburning” which can take place in the dilute catalyst phase, in the cyclones or in the flue gas lines. Afterburning has been known to cause significant damage to plant equipment. CO to CO₂ combustion promoters are commonly added to the FCC catalyst inventory of the regenerator with the objective to achieve a complete combustion of carbon monoxide in the regenerator dense phase and thereby avoiding this afterburning. The combustion promoters are separate particles from the cracking catalyst particles. The combustion promoters will be circulated with the rest of the FCC catalyst inventory from the regenerator to the riser, to the stripper and back to the regenerator.

22. CO to CO₂ combustion promoters are commonly made from impregnation of Group VIII noble metal or metals, commonly platinum and/or palladium. A known disadvantage of noble metal based CO to CO₂ combustion

promoters is that relatively large amounts of noble metal are required to achieve the desired CO combustion in the FCC process.

23. As of 2018, there were two commonly-known structures of catalytic particles—uniform distribution and eggshell distribution. Uniform distribution results in impregnation of Group VIII noble metals in a homogeneous concentration throughout the catalyst particle. Eggshell distribution results in a particle wherein there is a greater concentration of noble metals on the outer shell or outer region of the particle and decreasing concentration of noble metal in the core or “yolk” of the particle. By placing the active noble metal in a region near the surface, the detrimental diffusion limitations, *e.g.*, CO diffusion in the CO to CO₂ oxidation system, are reduced or even avoided. The cost of noble metals necessary for activity of the catalyst would have motivated a POSITA to select an eggshell distribution thereby reducing the overall amount of noble metal used, while retaining activity of the catalyst.

24. Another problem faced was the formation of nitrogen oxides (“NO_x”). NO_x forming reactions involve catalytic conversion of nitrogen-containing hydrocarbons into NO_x. *See* Babich. NO_x forming reactions oxidation of N-containing compounds such as ammonia (NH₃) are catalyzed by noble metals such as Pt or Pd. In general, the higher the loading of metal the higher will be the rates of CO oxidation and NO_x forming reactions. CO is a known inhibitor during its co-

oxidation with other compounds such as hydrocarbons. *See generally* Lang. Thus, another known advantage of the eggshell distribution as of the effective filing date of the '864 patent was that a reduced loading of the noble metal resulted in less generation of NO_x as the noble metal can catalyze NO_x forming reactions. Further, the noble metal will sinter in time making the combustion promoter less active for CO to CO₂ oxidation. The sintered particle will, however, still remain in the catalyst inventory of a FCC unit and continue to catalyze the NO_x forming reactions. The sintered noble metal may promote the NO_x forming reactions better than the fresh, non-sintered noble metal. The sintered metal within the entire particle will promote the NO_x forming reactions because these reactions are less diffusion limited.

25. Other properties of these catalyst particles are well known in the art.

26. The loading of active metal catalyst within a porous catalyst pellet or particle is known in the art to have a promotional effect on the reaction rate. It is generally known in the art that the balance between the rate of reaction and rate of diffusion is quantified by the Thiele modulus, ϕ , defined as:

$$\phi = d(k/D)^{1/2}$$

where d is the particle diameter or diffusion distance, k is the first-order rate constant, and D is the reactant diffusivity. The rate constant k may be increased by increasing the catalyst loading. For a diffusion controlled, first-order reaction in a

catalytic slab with diffusion distance d , the rate r (mole/cm³ s) is given by the equation:

$$r = k C_f \tanh(\phi)/\phi$$

where C_f is the gas phase concentration of reactant (mole/cm³). The rate of reactant converted (F) is the product of the rate and the volume of the particle, V (cm³):

$$F = rV$$

Typical values of ϕ are as small as 0.01 and as large as 10 or higher. For $\phi > 10$, the (diffusion limited) rate simplifies to:

$$r = (kD)^{1/2}C/d$$

whereas for $\phi < 0.1$, the (kinetic limited) rate equation is given by:

$$r = kC$$

It is generally known that a properly designed catalyst $\phi \sim 1$. Regardless, an increase in the catalyst loading will lead to an increase in the rate.

27. It is known in the art that the active ingredient in a catalyst may be distributed in a way that increases the rate of reaction. For a reaction whose rate increases with increasing reactant concentration (positive order reaction) concentrating the catalyst near the surface of the particle will increase the rate. For a reaction whose rate decreases with increasing reactant concentration (negative order reaction) concentrating the catalyst near the center of the particle will

increase the rate. This approach of concentrating the catalyst near the surface (eggshell) or in the core (egg yolk) is done if the reaction is known to be diffusion controlled.

28. For typical temperature conditions of a FCC regenerator, the regeneration is diffusion controlled, or $\phi \gg 10$. Further, under these conditions the CO oxidation reaction is known to be positive order. Thus, the concentrating of a fixed amount of FCC catalytic material (promoter) into a narrow region near the surface of the catalyst particle will serve to increase the CO oxidation rate, or lower the requisite temperature to achieve the same rate.

29. We consider three particles, one in which the active material is uniformly distributed within the support and the second and third for which the fixed amount of active material is increasingly concentrated within a surface layer (eggshell). The case considered is of a slab catalyst of area $S = 0.1 \text{ cm}^2$ and half-thickness 0.1 cm. The following table provides the values of interest:

D	C	k	d	ϕ	$\tanh(\phi)/\phi$	r	F
cm ² /s	mole/cm ³	1/s	cm			10 ⁻⁶ mole/cm ³ s	10 ⁻¹⁰ mole/s
1.00E-02	1.00E-08	1.00E+01	1.00E-01	3.16E+00	3.15E-01	3.15E-02	3.15E+00
1.00E-02	1.00E-08	1.00E+02	1.00E-02	1.00E+00	7.60E-01	7.60E-01	7.60E+00
1.00E-02	1.00E-08	1.00E+03	1.00E-03	3.16E-01	9.65E-01	9.65E+00	9.65E+00

The examples considered have 10x and 100x concentrating of active material in a shell of 0.1x and 0.01x narrower shell. The net effect is seen that with increased active material concentrating / shell narrowing, the rate of consumption increases

by a factor of 2.4x and 3.06x, respectively. This example demonstrates the advantage of concentrating the active material in a shell near the surface for a positive-order reaction.

A. Eggshell Catalyst

30. Eggshell catalysts were known in the art as of the earliest priority date, April 2, 2018, of the '864 patent.

31. For example, Miura discloses “a metal oxide particle comprising a core part relatively rich in a component originated in the population of first colloid particles and a surface layer relatively rich in a component originated in the population of second colloid particles can be obtained.” Miura, [0014]. Miura therefore discloses the surface layer (*i.e.*, outer region) is relatively rich in particles “selected from the group consisting of alumina, ceria, zirconia and titania colloid particles group,” and may be ceria. *Id.*, [0023]-[0026]. Miura further discloses that a “noble metal such as platinum, rhodium and palladium is supported on . . . the surface layer” wherein platinum is more the most preferable. *Id.* [0048], [0072]. Miura depicts this structure—referred to in the art as an “eggshell”— in FIG. 2, depicting a surface layer (12) of particulate support comprising CeO₂ which covers an entire core part (11) formed of ZrO₂, and a noble metal (13), such as platinum, supported on the particulate support. *Id.*, FIG 2, [0068].

32. Similarly, Lin discloses “an eggshell catalyst and process for preparation of the same,” including “single- or multiple-metal eggshell of the finished catalyst.” Lin, 1. Lin further teaches that the “eggshell” structure is known in the art as and discloses an eggshell catalyst wherein the “[m]etal is distributed on the outer layer of the support (with eggshell shape), which is usually used in fast reactions and capable of improving the selectivity and yield of the desired products.” *Id.*, 1-2. Lin teaches that the metal catalysts with eggshell active metal profile “preferably comprises Pd, Ni, Co, Ho, Cu, Pt, Fe, Ag, Tr, Pb, Re, Ti, Sn, V, and Zn, etc.” *Id.*, Abstract, 3. Lin provides an example wherein the preparation of the catalyst “with linear decrease of Pd metal distribution from outer layer toward spherical core.” *Id.*, 10.

33. Espinoza is directed to a catalyst comprising an inner core and outer layer wherein the outer layer contains catalytically active metal, such as a Group VIII metal, which is *not* deposited in the core of the particle. Espinoza, 4:26-47. Espinoza teaches the cost efficiency of loading the catalytically active metal on the outer layer of the particle and identifies that “uniform dispersion inherently exiles a substantial amount of catalytic metal to the deep internal surfaces or ‘core’ of a support.” *Id.*, 2:37-44.

B. Particle Size

34. I understand that the applicant of the '864 patent submitted that the term "microsphere" is "a term of art, the metes and bound of which are readily understood by one of ordinary skill in the art," and supported this argument with a declaration by Dr. Natalie Herring, Ph.D. '864 Prosecution History, 94, 143-44. I understand that the applicant defined "microsphere sized porous particles" as those particles "*having a diameter of less than 1 mm.*" *Id.*, 85.

35. I understand the '864 patent further acknowledges that "CO to CO₂ promoters are *well known*" and "are *commonly made* from impregnation of Group VIII noble metal or metals, commonly platinum and/or palladium, onto a porous alumina and/or other substrate *microspheres of average particle size 60 to 90 microns.*" '864 patent, 1:26, 1:62-66; *see also* '864 Prosecution History, 94, 143-44. I agree with the applicant for the '864 patent that such CO to CO₂ promoters (*i.e.*, oxidation catalysts) were well known at the time of the earliest filing date of the '864 patent.

36. As admitted by the applicant for the '864 patent, microsphere particle sizes were widely implemented in the art before the earliest filing date of the '864 patent. For example, Baker teaches that the "layer has an average thickness which is less than half the radius of the particle, for example less than 25 microns." *Id.*, 2:41-58. As to the average particle size, Baker teaches that the catalyst support is

“typically more than 20 nanometers in mean diameter and may be up to about 100 nanometers or more” and preferably “about 40 to 80 nanometers.” *Id.*, 4:8-17.

Baker further teaches that the support particles are “microspheroidal.” *Id.*, 1:60-67, 3:34-46. Baker specifically teaches that the catalyst has the following particle size distribution:

0 to 20 microns	0-30 wt %
20 to 44 microns	0-60 wt %
44 to 88 microns	10-80 wt %
88 to 106 microns	0-80 wt %
>106 microns	0-40 wt %
>300 microns	0-5 wt %

id., 3:16-33. Baker further teaches that “[p]article sizes and particle size distributions may be measured by an automated laser device such as a Microtrac X100.” *Id.* A POSITA would have recognized that an automated laser device such as the specific example Baker provides (Microtrac X100) is a laser diffraction device. Further, a POSITA would have understood that laser diffraction is a common and well-known technique for measuring particle size.

To determine the average particle size based on this table, a POSITA would need to calculate the weighted mean particle size. This is done by multiplying the midpoint of each size range by the weight percentage and then summing these values and dividing by the total weight percentage. To first calculate the midpoint for each size range, a POSITA would take the average of the lower and upper limits as follows:

- 0 to 20 microns: midpoint = $(0+20)/2 = 10$ microns
- 20 to 44 microns: midpoint = $(20+44)/2 = 32$ microns
- 44 to 88 microns: midpoint = $(44+88)/2 = 66$ microns
- 88 to 106 microns: midpoint = $(88+106)/2 = 97$ microns
- >106 microns: assuming the range from 106 microns to the next upper range of >300 microns, a POSITA would have made a reasonable assumption that the midpoint would be equal to $(106+300)/2 = 203$ microns
- >300 microns: given there is no upper range provided for this set of sizes, a POSITA would have made a reasonable assumption to use 350 microns as the midpoint. In particular, a POSITA would have recognized that Baker discloses a catalyst composition preferably used in a fluid bed application, which a POSITA would understand is typically an application using smaller particles. Baker, 3:11-15; *see also* Espinoza, 7:51-67. In such an application and in light of Baker's disclosure of the range of particle diameters, a POSITA would have made an assumption of the upper limit of particle size diameter at approximately 400 microns; therefore, the assumption of a midpoint of 350 microns of the upper range of particle sizes is reasonable.

A POSITA would have then multiplied each midpoint by its corresponding weight percentage to get the weighted value as shown below:

- 0 to 20 microns: $10 \times 0.15 = 1.5$
- 20 to 44 microns: $32 \times 0.3 = 9.6$
- 44 to 88 microns: $66 \times 0.45 = 29.7$
- 88 to 106 microns: $97 \times 0.4 = 38.8$
- >106 microns: $203 \times 0.2 = 40.6$
- >300 microns: $500 \times 0.025 = 12.5$

Using the midpoint of the particle size range disclosed by Baker to calculate the weighted value is a reasonable method a POSITA would have employed. Next, a POSITA would have added the weighted values as shown below:

- $1.5 + 9.6 + 29.7 + 38.8 + 40.6 + 12.5 = 132.7$

Then, a POSITA would have divided by the total weight percentage to get the average particle size as shown below:

- $.15 + 0.3 + 0.45 + 0.4 + 0.2 + 0.025 = 1.825$
- $132.7 / 1.85 = 72.7$ microns

To conclude, Baker teaches an average particle size of approximately 73 microns.

Therefore, Baker teaches microsphere sized porous particles having an average diameter size of less than 1mm (1000 microns).

37. Miura discloses a range of average particle diameters of the metal oxide particles as, “less than 10 μm , less than 5 μm , less than 1 μm , less than 500 nm, less than 200 nm, less than 100 nm or less than 50 nm,” and teaches the benefits of small particle size. *Id.*, [0015], [0068]; therefore, Miura discloses particles having an average diameter size of less than 1mm. Miura teaches benefits of using small particle size in the disclosed combustion promoter. Miura, [0068].

38. Espinoza is instructive that a smaller particle size may be more appropriate in the application of fluidized catalysts whereas a larger particle size is appropriate in a fixed bed catalyst application. Espinoza, 7:51-67. Specifically, Espinoza teaches that particle size ranging from 0.5 mm to 0.25 mm are most useful in fluidized bed catalyst reactions. *Id.*, 7:51-67.

39. Lin teaches an example wherein a catalyst was prepared using “spherical particles with diameter of 2mm.” Lin, 5. A POSITA would have been motivated to adjust the size of the particles depending on the application. For instance, as was known in the art as of the critical date of the ’864 patent, as illustrated, for example, by Espinoza, a smaller particle size may be more appropriate in the application of fluidized catalysts whereas a larger particle size is appropriate in fixed bed catalyst applications. Espinoza, 7:51-67. Indeed, as admitted by Applicant in the ’864 patent itself and during its prosecution before the Patent Office, it was well understood in the industry that “CO to CO₂ promoters

are *well known*” and “are *commonly made* from impregnation of Group VIII noble metal or metals, commonly platinum and/or palladium, onto a porous alumina and/or other substrate *microspheres of average particle size 60 to 90 microns.*”

‘864 patent, 1:26, 1:62-66; *see also* ‘864 Prosecution History, 94, 143-44.

C. Surface Area

40. A POSITA would have appreciated other properties of microsphere particle size, namely, the particle’s surface area. For example, Baker discloses the surface area of support particles is typically “about 50 m²/g and may range up to about 200 m²/g . . . and may range up to about 800 m²/g.” Baker, 3:41-51, 4:18-28. Baker’s range overlaps with the claimed surface area of between 50 and 300 m²/g.

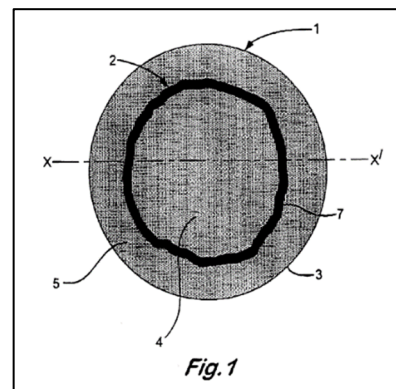
41. Likewise, Lin discloses “spherical particles with diameter of 2mm, surface area of 82.4 m²/g” and spherical γ -alumina particles with a surface area of 173 m²/g. Lin, 5, 10. Lin’s surface area disclosure also overlaps with the claimed surface area of between 50 and 300 m²/g.

D. Pore Volume

42. A POSITA would have appreciated that the pore volume of the catalyst is another physical property associated with microsphere particles. Baker discloses that a “typically suitable microspheroidal support particle has a pore volume (measured by nitrogen sorption) between about 0.2 and 0.7 cc/g.” *Id.*, 3:41-51, 4:18-28. Measurement of pore volume involves filling the pores with

fluid, either nitrogen or water, and calculating the pore volume based on the density of the fluid. A POSITA would have appreciated that pore volume is measureable by either method but nitrogen sorption is the more common and accurate method. The volume measurement cc/g is equivalent to mL/g. Therefore, Baker's pore volume overlaps with the claimed pore volume of between 0.05 and 0.50 mL/g.

43. Baker also discloses that the “catalytically active metal(s) may be impregnated in one or more steps onto the support particles in the form of precursor *salt solutions*” wherein the preferred medium is a *palladium compound in a suitable solvent*, such as water, carboxylic acids, alcohols, nitriles, or chlorinated solvents. *Id.*, 4:48-65. Baker further teaches that a “preferable method to impregnate salt solutions is an incipient wetness technique in which there is used a salt solution in an amount up to the volume of the pores of the support particles *without excess solution being used.*” *Id.*, 5:42-54. Baker explains the goal of this method to obtain a “desirable level of metal compounds, such as palladium” incorporated into the support particles on the outer edge (7) below the particle surface (3), as depicted in Figure 1. *Id.*, 5:42-54, 7:35-53. In order to incorporate a desirable level of metal compound into the support particle on the outer edge, the salt solution must be up to or less than the



total volume of the pores of the starting microsphere sized particles. For example, deviating from the teaching of Baker and using excess solution more than the total volume of the pores would prevent the deposition of the metal compound on the outer edge of the support particle. Moreover, Baker teaches a range of volume of salt solution that is less than or equal to the pore volume of the particles.

E. Equilibrium or Spent Catalyst

44. The '864 patent describes an equilibrium or spent catalyst as “obtained from a FCC process wherein fresh FCC catalyst has deactivated by some degree” such that the “catalyst particles may thus find a suitable second use as a CO to CO₂ combustion promoter.” '864 patent, 4:47-53.

45. Use of equilibrium or spent catalysts was known as of the effective filing date of the '864 patent and had been in use well before then. For example, Vaughn 290 discloses *recycled* particles that “are actually molecular Sieve-containing catalyst particles that have be used in a functioning manufacture or reaction System.” Vaughn 290, 9:55-65. Vaughn 290 further discloses that those particles “are recovered from the manufacture or reaction System and are recycled back into the catalyst manufacturing Scheme.” *Id.*; *see also id.*, 16:26-35.

46. A POSITA would have understood that the recycled catalyst disclosed in Vaughn 290 is an equilibrium or spent catalyst as described by the '864 patent. Indeed, Vaughn 290 teaches an equilibrium or spent catalyst is used in a process

wherein fresh catalyst as used in a first reaction is then recycled for use in a second catalyst reaction. Vaughn 290, 9:55-65, 16:26-35;

F. Inorganic Oxide Matrix

47. As described above, a POSITA would have understood that a common component of catalyst particles is porous inorganic oxide matrix. A POSITA would also have appreciated that cerium oxide and copper oxide are typical and well-known options for the inorganic oxide matrix.

48. For example, Miura discloses “a *metal oxide particle* comprising a core part relatively rich in a component originated in the population of first colloid particles and a surface layer relatively rich in a component originated in the population of second colloid particles can be obtained.” Miura, [0014]. Miura further discloses a surface layer (12) of particulate support comprising *cerium oxide* (CeO_2) which covers an entire core part (11) formed of ZrO_2 , and a noble metal (13), such as platinum, supported on the particulate support. *Id.*, FIG 2, [0068].

49. Likewise, Baker further teaches that the support particles include “alumina, silica-alumina, *ceria*, magnesia, titania, zirconia and *mixed oxides* and mixtures thereof,” and other oxides may be used including “other metals such as gold, *copper*, *cerium* and mixtures thereof.” *Id.*, 4:8-36, 4:66-5:12. The scope of Baker includes support particles comprising ceria oxide and copper oxide.

50. Lin also teaches the use of copper oxide. For example, Lin teaches that the metal catalysts with eggshell active metal profile “preferably comprises Pd, Ni, Co, Ho, **Cu**, Pt, Fe, Ag, Tr, Pb, Re, Ti, Sn, V, and Zn, etc.” *Id.*, Abstract, 3. Lin further teaches that *copper oxide* ($\text{Cu}(\text{NO}_3)_2$) is “used by means of various impregnation technologies to produce *non-uniformly distributed* Cr and *Cu metal in different state* on spherical Al_2O_3 support.” *Id.*, 2.

G. Attrition Index

51. A POSITA would have understood that the inorganic oxide matrix used in an eggshell catalyst structure forms the outer region of the eggshell. Thus, a POSITA would have appreciated that the selection of inorganic oxide matrix affects the attrition of the catalyst particles.

52. Attrition is regarded as the degradation of the exterior surface of the catalyst particles. During fluidization processes, such as FCC processes, the catalyst particles are mechanically degraded by attrition, which leads to the generation of fines. These fines bypass the cyclones used for separation in FCC processes, and a proportion can enter the atmosphere, which has health and environmental implications. The attrition of these catalyst particles necessitates their periodic replacement; this constitutes a significant cost factor in FCC processes.

53. Attrition can be quantified via multiple methodologies. For example, the '864 patent describes the ASTM D-5757 standard test method. This test method covers the determination of the relative attrition characteristics of FCC catalysts by means of air jet attrition. *See* ASTM Standard. As the '864 patent recognizes, the “skilled person will be able to find the optimal Attrition Index for the CO to CO₂ combustion promoter depending for example on the desired residence time and the influence of the FCC unit itself to the attrition of the FCC catalyst inventory.” ‘864 patent, 6:53-63. Further, the '864 patent acknowledges that “[t]his process of finding the optimal Attrition Index may for example be an empirical iteration.” *Id.*

54. Other attrition test methodologies were available as of the effective filing date of the '864 patent. The air-jet attrition test is the basis for the ASTM standard. Wu et al. developed a model to analyze data obtained using an air-jet apparatus for measuring attrition resistance. *See* Wu. Cocco et al. describes the alternative jet-cup attrition test method. This method has the advantage that less catalyst sample and was able to assess the attrition resistance of a powder. *See* Cocco. This is sometimes referred to as the Davison jet cup attrition method and is commonly used to rank particles in terms of their attrition resistance in a particular application.

55. Vaughn 516 discloses obtaining a catalytic composition containing a molecular sieve wherein the attrition resistance of the composition is measured using an Attrition Rate Index (ARI) using a hardened steel attrition cup. Vaughn 516, [0130]. Vaughn 516 further teaches that the catalyst composition of an *average particle size from 53 to 125 microns* and “*an ARI less than 15 weight percent per hour, preferably less than 10 weight percent per hour, more preferably less than 5 weight percent per hour*, and even more preferably less than 2 weight percent per hour, and most preferably less than 1 weight percent per hour.” *Id.*, [0131]. The ASTM D-5757 value disclosed in the '864 patent is comparable to the ARI value used in Vaughn 516. ASTM Standard. Vaughn 516 teaches an overlap of the claimed average particle size (53-105 microns) and claimed attrition value (10-15).

56. Peters discloses combustion promoters for use in FCC catalytic processes such that when the promoter is used as an additive particulate, the *average particle size is 20-200 microns* and the attrition value of the additive particles measured by the *Davison attrition index (DI) is “about 0-45, more preferable about 0-15.”* Peters, 3:9-20. The ASTM D-5757 value disclosed in the '864 patent is comparable to the DI value used in Peters. ASTM Standard. Peters teaches an overlap of the claimed average particle size (40-105 microns) and claimed attrition value (5-25 or, preferably, 5-15).

A Person of Ordinary Skill in the Art Would Have Been Motivated To Apply a Microsphere Particle Size to an Eggshell Catalyst

57. A POSITA would have appreciated the benefits of adjusting the size of the catalyst particles depending on the application. In particular, a POSITA would have considered the use of microsphere particles in an eggshell structure combustion promoter. For example, Espinoza is instructive that a smaller particle size may be more appropriate in the application of fluidized catalysts whereas a larger particle size is appropriate in a fixed bed catalyst application. Espinoza, 7:51-67. Specifically, Espinoza teaches that particle size ranging from 0.5 mm to 0.25 mm are most useful in fluidized bed catalyst reactions. *Id.*, 7:51-67.

58. As of 2018, and acknowledged by the Applicant himself in the '864 patent, eggshell catalyst structures were well-known in the art with particle sizes larger than the claimed "microspheres" and, likewise, acknowledged that CO to CO₂ combustion promoters were "commonly made from impregnation of Group VIII noble metals or metals, commonly platinum and/or palladium, onto a porous alumina and/or other substrate microspheres of average particle size 60 to 90 microns." WRG-1001 at 4:18-24 (eggshell particles), 1:62-67 (microsphere size). As described above, Baker teaches microsphere sized porous particles having an average diameter size of less than 1mm. A POSITA would have recognized that particles with an average particle size less than 1mm may be used in conjunction with the combustion promoter of Miura. For example, a POSITA would have

recognized that Miura and Baker both teach similar catalyst structures and components of the combustion promoters, including silica, aluminum, and Group VIII metals and Miura teaches benefits of small particle diameter size. Miura, [0068]. By incorporating the specific particle size range of Baker to Miura, the properties of Miura's catalyst can be further improved through the specific particle size teachings of Baker.

59. A POSITA would have been further motivated to pursue this implementation of Baker's specific particle size into Miura's catalyst as doing so is merely the application of known techniques (*e.g.*, using small particles) to a known structure (*e.g.*, combustion promoter material) to yield predictable results (*e.g.*, improved performance). And a POSITA would have expected success in the Miura-Baker combination given that both Miura and Baker already describe using sub-1mm particles for improved catalytic performance.

60. Likewise, Lin teaches "eggshell catalysts have been widely employed in the industrially selective hydrogenation" and, in particular, discloses "an eggshell-shaped catalyst for use in selective reduction or oxidation," including, for example, oxidation of CO. *Id.*, 1-2, 13. Lin further teaches an example wherein a catalyst was prepared using "spherical particles with diameter of 2mm." *Id.*, 5. While Lin does not expressly teach "microsphere" particle size of less than 1mm, a POSITA would have appreciated nevertheless the use of 2mm particles in

combination with the improved catalytic performance of the disclosed eggshell-shaped catalyst. *Id.*, 1-2, 13. A POSITA would have also considered the similar eggshell structure of the catalyst disclosed by Lin and the similar structure taught by Baker and thereby would have been motivated to use the disclosed particle sizes taught by Baker. Likewise, Espinoza teaches “[s]mall-size support particles (less than 0.5 mm, preferably less than 0.25 mm) tend to be more useful in fluidized beds.” WRG-1011, 7:63-65.

61. A POSITA would have also recognized that the particles with an average particle size less than 1mm may be used in conjunction with the combustion promoter of Lin. *Id.* For example, Lin and Baker both teach similar catalyst structures and similar components, including silica, aluminum, and Group VIII metals and the improved selectivity and yield of the eggshell shaped catalyst. Lin, 1-2. By incorporating the specific particle size range of Baker to Lin, a POSITA would have recognized that the properties of Lin’s combustion promoter can be further improved through the specific particle size teachings of Baker.

62. A POSITA would have been further motivated to pursue this implementation of Baker’s specific particle size into Lin’s eggshell catalyst as doing so is merely the application of known techniques (*e.g.*, using small particles) to a known structure (*e.g.*, combustion promoter material) to yield predictable results (*e.g.*, improved performance). And a POSITA would have expected

success in the Lin-Baker combination given that both Lin and Baker already describe using sub-1mm particles for improved catalytic performance, much like the '864 patent admits was already known in the art.

63. A POSITA would thereby have been motivated to use particles with diameters less than 1mm, as disclosed by Baker, to prepare an eggshell-shaped catalyst, as described by Lin, in light of the small (2mm) particle size already disclosed by Lin.

A Person of Ordinary Skill in the Art Would Have Been Motivated To Apply an Eggshell Catalyst Structure to a Spent or Equilibrium Catalyst

64. A POSITA would have appreciated the benefits of using a spent or equilibrium catalyst in a combustion promoter. In particular, a POSITA would have understood the benefits of recycling catalyst composition as minimizing waste and increasing efficiencies of both environmental and economic constraints.

65. As of 2018, spent or equilibrium catalysts were well-known in the art as was the eggshell structure. As described above, Vaughn 290 discloses a catalyst for use in a variety of catalytic reaction processes using *recycled* particles that “are actually molecular Sieve-containing catalyst particles that have be used in a functioning manufacture or reaction System.” Vaughn 290, 9:55-65. A POSITA would understand that “the recovery and use of the attrition particles in [a] catalyst is beneficial in minimizing waste, thereby reducing problems relating to both environmental and economic constraints.” Vaughn 290, Abstract;

66. A POSITA would have recognized that the efficiencies and benefits of recycling catalyst material in combination with eggshell catalyst, such as those disclosed in Miura and Lin. Likewise, a POSITA would have appreciated the similarities of the structure disclosed by Baker wherein the “catalyst composition comprising support particles hav[e] at least one catalytically active metal distributed therein” wherein the “catalyst composition [is] suitable for the manufacture of vinyl acetate may also comprise . . . promoters.” Baker, 1:60-67, 4:66-5:12. Therefore, a POSITA would have appreciated that similar efficiencies would be achieved using the microsphere particles of Baker in a recycled process described in Vaughn 290.

67. A POSITA would have been further prompted to pursue the efficiencies of Vaughn 290 as doing so is merely the application of known techniques (*e.g.*, recycling combustion promoter particles) to a known structure (*e.g.*, the combustion promoter particles) to yield predictable results (*e.g.*, minimizing waste). And a POSITA would have expected success in combining the recycled particles in a catalyst having eggshell structure given that both Miura and Lin already describe catalyst for use in a variety of catalytic reaction processes, including a CO to CO₂ combustion promoter. *See* Miura, Abstract, [0014]; Lin, 1-2; Baker, 1:60-67, 4:66-5:12; Vaughn 290, Abstract, 2:43-45.

**A Person of Ordinary Skill in the Art Would Have Been Motivated To
Measure the Attrition Value of an Eggshell Catalyst**

68. A POSITA would have been motivated to select cerium oxide or copper oxide as the inorganic oxide matrix in an eggshell catalyst. In particular, a POSITA would have understood that cerium oxide and copper oxide were common components of an eggshell catalyst and such outer layer of the catalyst would result in a predictable attrition value. A POSITA would have also understood that a low attrition index is desirable in a combustion promoter.

69. As of 2018, eggshell catalysts comprising cerium oxide or copper oxide were well-known in the art. For example, each of Miura, Baker, and Peters teaches the use of similar components of the combustion promoter, namely, the use of ceria as the preferred oxide component as the outer layer (most susceptible to attrition) of the eggshell structure disclosed by Miura or non-uniform structure disclosed by Baker. *See* Miura, [0068]; Peters, 1:49-60; Baker, 4:8-36, 4:66-5:12. Lin likewise teaches the use of similar components of the combustion promoter, namely, the use of copper as the preferred oxide component as the outer layer (most susceptible to attrition) of the eggshell structure disclosed by Lin. *See* Lin, Abstract, 2, 3; Baker, 4:8-36, 4:66-5:12; Peters, 1:49-60. A POSITA would have understood the similar properties of cerium oxide and copper oxide in application to catalytic reactions.

70. Peters explicitly identifies the attrition index value of the combustion promoter composition. Peters, 3:9-20. Peters discloses combustion promoters for use in FCC catalytic processes that when the promoter is used as an additive particulate, the *average particle size is 20-200 microns* and the attrition value of the additive particles measured by the *Davison attrition index (DI) is “about 0-45, more preferable about 0-15.”* Peters, 3:9-20.

71. By incorporating the specific attrition index teachings of Peters to the eggshell structured catalyst of Miura or non-uniform structure of Baker, a POSITA would have recognized that the attrition value of the eggshell catalyst, using the same cerium oxide as the outer layer of the combustion particles, would have been similar or equivalent to that disclosed in Peters. A POSITA would have been further prompted to pursue the optimal attrition index of the combustion promoter particles as doing so is merely the application of known techniques (*e.g.*, standard attrition measurement) to a known structure (*e.g.*, the combustion promoter particles) to yield predictable results (*e.g.*, improved attrition properties). '864 patent, 6:53-63. And a POSITA would have expected success in the combination of an eggshell catalyst with cerium oxide having a particular attrition value given that using cerium oxide is a known and preferred metal oxide component of the combustion promoter. *See* Miura, [0068]; Peters, 1:49-60. Likewise, a POSITA would have expected success in the eggshell catalyst of Lin combined with the

particular attrition value given the similar properties of cerium oxide and copper oxide in application to catalytic reactions.

72. Similarly, a POSITA would understand that catalyst material should be durable and attrition-resistant and therefore a low attrition index is desirable, while reducing NO_x emissions. In particular, a POSITA would have understood that Group VIII metals, including platinum and palladium, were common catalytic components of an eggshell catalyst and an eggshell structure comprises a low concentration of the noble metal in the core of the eggshell. Vaughn 516 teaches the use of Group VIII metals, including platinum and palladium, such that the concentration of the Group VIII metal is low in the support material. Vaughn 516, [0108], [0164]. Vaughn 516 specifically teaches that this design choice is effective in reducing overall catalyst cost and “increasing catalyst strength such as crush strength and attrition resistance.” Vaughn 516, [0106].

73. Vaughn 516 explicitly identifies the attrition index value of the combustion promoter composition. Vaughn 516, [0131]. Vaughn 516 further teaches that the catalyst composition of an *average particle size from 53 to 125 microns* and “*an ARI less than 15 weight percent per hour, preferably less than 10 weight percent per hour, more preferably less than 5 weight percent per hour, and even more preferably less than 2 weight percent per hour, and most preferably less than 1 weight percent per hour.*” *Id.*, [0131].

74. By incorporating the specific attrition index teachings of Vaughn 516 to the eggshell structured catalyst of Miura or non-uniform structure of Baker, a POSITA would have recognized that the attrition value of the eggshell catalyst, using the same catalytic components, would have been similar or equivalent to that disclosed in Vaughn 516. A POSITA would have been further prompted to pursue the optimal attrition index of the combustion promoter particles as doing so is merely the application of known techniques (*e.g.*, standard attrition measurement) to a known structure (*e.g.*, the combustion promoter particles) to yield predictable results (*e.g.*, improved attrition properties). '864 patent, 6:53-63. And a POSITA would have expected success in the combination of an eggshell catalyst having a particular attrition value given that using platinum or palladium are a known catalytic component of the combustion promoter. *See* Miura, [0068]; Vaughn 516, [0108], [0164]. Likewise, a POSITA would have expected success in the eggshell catalyst of Lin combined with the particular attrition value given the similar properties of catalytic reactions.

Prior Art Analysis

**H. [GROUND 1] – CLAIMS 1, 3, 6, 7, 12-19, & 21 ARE
OBVIOUS OVER MIURA IN VIEW OF APPLICANT
ADMITTED PRIOR ART (AAPA)**

75. It is my opinion that a POSITA would have found claims 1, 3, 6, 7, 12-19, and 21 to be obvious over Miura and AAPA, as I discuss in the following sections.

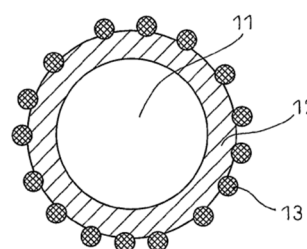
1. Overview of Miura

76. Miura is directed to “an exhaust gas purifying catalyst and process for producing a metal oxide particle” wherein the particle comprises “a core part relatively rich in a component originated in a population of first colloid particles and a surface layer relatively rich in a component originated in the population of second colloid particles.” Miura, Abstract, [0014]. Miura describes its invention as relating “to a process for producing a metal oxide particle and, more specifically, the present invention relates to a process for producing a metal oxide particle preferably used as an exhaust gas purifying catalyst by loading a noble metal thereon.” *Id.*, [0001]. Miura further describes that “[t]he exhaust gas from internal combustion engines, such as automobile engines, contains nitrogen oxide (NO_x), carbon monoxide (CO), hydrocarbon (HC) and the like. These substances can be purified by an exhaust gas purifying catalyst capable of oxidizing CO and HC and, at the same time, reducing NO_x. As for representative exhaust gas purifying catalysts, three-way catalysts where a noble metal such as platinum (Pt),

rhodium (Rh) and palladium (Pd) is supported on a porous metal oxide support such as γ -alumina are known.” *Id.*, [0002]. In addition, Miura describes that “[t]he metal oxide support may be formed of various materials but, in order to obtain a large surface area, alumina (Al_2O_3) has been heretofore generally used. However, in recent years, for accelerating purification of the exhaust gas by using chemical properties of the support, it has been proposed to use various other materials such as ceria (CeO_2), zirconia (ZrO_2) and titanium (TiO_2) in combination with, or not in combination with, alumina.” *Id.*, [0003].

77. Miura describes that the core part of the metal oxide particles may be “relatively rich in zirconia, alumina or titania” and the surface layer may be “relatively rich in ceria.” *Id.*, [0025]. Figure 2 of Miura depicts an embodiment comprising a core part rich in zirconia (11), a surface layer rich in ceria (12), and a noble metal, platinum (13), forming the particulate support of the surface layer. *Id.*, FIG. 2, [0068]. Miura recognizes the “excellent gas purifying performance” achieved by this embodiment. *Id.*

Fig. 2



2. Applicant Admitted Prior Art (AAPA)

78. In the '864 patent, the applicant admitted that “CO to CO_2 promoters are *well known*” and “are *commonly made* from impregnation of Group VIII noble

metal or metals, commonly platinum and/or palladium, onto a porous alumina and/or other substrate ***microspheres of average particle size 60 to 90 microns.***”

’864 patent, 1:26, 1:62-66; *see also* ’864 File History, 94, 143-44.

Notwithstanding applicant’s admission that microspheres of average particle size 60 to 90 microns were well known and that such particles were used in CO to CO₂ promoters (*i.e.*, oxidation catalysts) and made from impregnation of Group VIII noble metal or metals, commonly platinum and/or palladium, onto a porous alumina and/or other substrate, applicant alleged that such impregnation “results in a uniform distribution of the Group VIII noble metal throughout the internal and external surfaces of the porous microsphere.” ’864 patent, 1:67-2:3. But as discussed throughout this declaration, many prior art references, prior to the earliest effective filing date of the ’864 patent, showed that CO to CO₂ combustion promoters made with the well-known microsphere particles had non-uniform distribution of the metals, such as those claimed by the ’864 patent.

79. Likewise, the applicant admitted during prosecution that a POSITA would be familiar with “microspheres” in the context of CO to CO₂ combustion promoters as “***spherical particles as small as 1 micron in diameter and as large as 1,000 microns (1 mm).***” ’864 File History, 94 (internal citations omitted).

3. Analysis

(i) Claim 1

[1pre] A CO to CO₂ combustion promoter comprising microsphere sized porous particles, each microsphere sized porous particle having a diameter of less than 1mm, and independently comprising:

80. To the extent the preamble is deemed to be limiting, Miura-AAPA renders obvious the preamble. Miura discloses “an exhaust gas purifying catalyst and a process for producing a metal oxide particle comprising multiple species of metal oxides and capable of satisfactorily exerting the properties of respective metal oxides.” Miura, Abstract. Miura further discloses that the disclosed exhaust purifying catalyst is capable of oxidizing CO (i.e., converting CO to CO₂). *Id.*, [0002]. Miura additionally discloses a range of average particle diameters of the metal oxide particles as, “less than 10 μm , less than 5 μm , less than 1 μm , less than 500 nm, less than 200 nm, less than 100 nm or less than 50 nm,” and teaches the benefits of small particle size. *Id.*, [0015], [0068]. Therefore, Miura discloses a CO to CO₂ combustion promoter including microsphere sized particles having an average diameter size of less than 1mm. While Miura discloses particles having an average diameter size of less than 1mm, Miura discloses particle sizes ranging from 10 μm and smaller. Miura thereby discloses particle sizes on a different scale of magnitude from the upper range of the preamble of the claim. Regardless, a POSITA would have been familiar with particle sizes in the 1mm and tens of microns range used in combination with combustion promoters. Indeed, the

applicant of the '864 Patent admitted that microsphere sized particles are well known in the art and were commonly used as CO to CO₂ combustion promoters. *See, e.g., '864 patent, 1:62-66* (“Such CO to CO₂ promoters are ***commonly made*** from impregnation of Group VIII noble metal or metals, commonly platinum and/or palladium, onto a porous alumina and/or other substrate ***microspheres of average particle size 60 to 90 microns.***”).

81. To the extent Miura does not explicitly disclose the preamble, the applicant admitted that CO to CO₂ combustion promoters were well known in the art and “are commonly made from impregnation of Group VIII noble metal or metals, commonly platinum and/or palladium, onto a porous alumina and/or other substrate microspheres of average particle size 60 to 90 microns.” ‘864 patent, 1:62-2:3. Thus, particles having an average diameter size of less than 1mm, like those disclosed in Miura, were known for use in CO to CO₂ combustion promoters. Likewise, the applicant admitted during prosecution that a POSITA would be familiar with “microspheres” in the context of CO to CO₂ combustion promoters as ***“spherical particles as small as 1 micron in diameter and as large as 1,000 microns (1 mm).”*** ‘864 File History, 94 (internal citations omitted). A POSITA would thereby have been motivated to use particles less than 1mm in diameter in a CO to CO₂ combustion promoter.

[1a] silica, alumina, or mixtures thereof; and

82. Miura discloses a combustion promoter that includes silica, alumina, or mixtures thereof. For example, Miura discloses that the “metal oxide support may be formed of various materials but, in order to obtain a large surface area, *alumina* (Al_2O_3) has been heretofore generally used.” Miura, [0003]. Miura further discloses “a metal oxide particle comprising a core part relatively rich in a component originated in the population of first colloid particles” wherein the “population of first colloid particles” may be alumina particles and, more specifically, may be *γ -alumina* particles. Miura, [0014], [0023]-[0026].

83. Moreover, the applicant admitted that CO to CO_2 combustion promoters are well known in the art and “are commonly made from impregnation of Group VIII noble metal or metals, commonly platinum and/or palladium, onto a porous alumina and/or other substrate microspheres of average particle size 60 to 90 microns.” ’864 patent, 1:62-2:3.

[1b] one or more Group VIII noble metals distributed in the particle as an eggshell such that a higher concentration of the one or more Group VIII noble metals is present in the outer region of the microsphere sized porous particle as compared to the concentration of the one or more Group VIII noble metals in the centre of the microsphere sized porous particle.

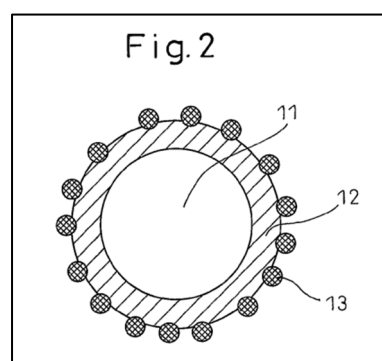
84. Miura discloses a combustion promoter comprising one or more Group VIII noble metals, the metals distributed in the particle as an eggshell such that a higher concentration of the one or more Group VIII noble metals is present in the outer region of the microsphere sized porous particle as compared to the

concentration of the one or more Group VIII noble metals in the centre of the microsphere sized porous particle. For example, Miura discloses that “[t]he present invention relates to a process for producing a metal oxide particle and, more specifically, the present invention relates to a process for producing a metal oxide particle preferably used as an exhaust gas purifying catalyst by loading a noble metal thereon.” Miura, [0001]. Miura further discloses that “[t]he exhaust gas from internal combustion engines, such as automobile engines, contains nitrogen oxide (NO_x), carbon monoxide (CO), hydrocarbon (HC) and the like. These substances can be purified by an exhaust gas purifying catalyst capable of oxidizing CO and HC and, at the same time, reducing NO_x. As for representative exhaust gas purifying catalysts, three-way catalysts where a noble metal such as platinum (Pt), rhodium (Rh) and palladium (Pd) is supported on a porous metal oxide support such as γ -alumina are known.” Miura, [0002].

85. Miura further discloses that “[a] noble metal such as platinum, rhodium and palladium is supported on the metal oxide particle obtained by the process of the present invention, and thereby an exhaust gas purifying catalyst can be produced. In the exhaust gas purifying catalyst produced, the noble metal can be supported mainly on the surface layer, because the metal oxide particle obtained by the process of the present invention can have a core part and a surface layer.” Miura, [0048]. Miura discloses that the “noble metal may be loaded on the metal

oxide particle by any known method, for example, by a method of impregnating metal oxide particles with a solution containing a salt and/or a complex salt of noble metal, and drying and then firing it. The amount of the noble metal supported on the metal oxide particle may be from 0.01 to 5 mass %, particularly from 0.1 to 2 mass %, based on the metal oxide particle.” Miura, [0049].

86. Miura discloses “a metal oxide particle comprising a core part [11, shown in Fig. 2] relatively rich in a component originated in the population of first colloid particles and a surface layer [12, shown in Fig. 2] relatively rich in a component originated in the population of second colloid particles can be obtained.” Miura further



discloses that the metal oxide particle is porous. Miura, [002], [0014], Fig. 2.

Miura discloses that the surface layer 12 (i.e., outer region) is relatively rich in particles “selected from the group consisting of alumina, ceria, zirconia and titania colloid particles,” and may particularly be ceria. *Id.*, [0023]-[0026], Fig. 2. Miura notes that the term “relatively rich” to describe the composition of the core part and surface layer is used with respect to the molar fraction based on the total molar number of metals in each of the core part and the surface layer. *Id.*, [0016].

87. As discussed above, Miura further discloses that a “noble metal [13, shown in Fig. 2] such as platinum, rhodium and palladium is supported on the

metal oxide particle. . . [and] mainly on the surface layer [12].” Miura, [0048], [0072], Fig. 2. Miura discloses that “[t]he noble metal may be loaded on the metal oxide particle by any known method, for example, by a method of impregnating metal oxide particles with a solution containing a salt and/or a complex salt of noble metal.” *Id.*, [0049]. Miura further discloses that “[t]he amount of the noble metal supported on the metal oxide particle may be from 0.01 to 5 mass %, particularly from 0.1 to 2 mass % based on the metal oxide particle.” *Id.*

88. A POSITA would have understood that the noble metal loaded on the metal oxide particle would disperse into the surface layer [12] or outer shell because the particle is porous. *Id.*, [0002]. Further, a POSITA would have understood that not only is the content (*i.e.*, mass) of the noble metal higher in the outer region [12] compared to the inner region [11] but also the concentration (*i.e.*, mass/volume) and/or weight percentage (*i.e.*, mass/mass)¹ of noble metal is higher in the outer region compared to the inner region. Miura depicts this resulting

¹ A POSITA would have recognized that concentration of noble metals is often given as wt.% which is effectively mass/total mass x 100. This is often called the metal loading. It is my understanding from the Prosecution History that the Patent Office defined concentration as “mass/volume.” *See* ’864 Prosecution History at 212. But I also understand that Patent Owner has asserted that concentration means “mass per mass,” WRG-1016, which as I noted above would be a weight percent (mass/total mass x 100). Under either construction, it is my opinion that Miura discloses or renders obvious a higher concentration of the one or more Group VIII noble metals is present in the outer region of the microsphere sized porous particle as compared to the concentration of the one or more Group VIII noble metals in the centre of the microsphere sized porous particle.

structure—referred to in the art as an “eggshell”— in Fig. 2, depicting a surface layer (12) of particulate support comprising CeO_2 which covers an entire core part (11) formed of ZrO_2 or, alternatively, alumina, and a noble metal (13), such as platinum, supported on the particulate support. Miura, FIG 2, [0068], [0023]-[0026].

89. Miura further provides several examples wherein the noble metal Pt (1% by weight) is incorporated into the surface layer composed of CeO_2 and the core part composed on ZrO_2 , lacking any content or concentration of Pt. Miura, [0098]-[0140]. In this manner, as shown and described with respect to Fig. 2, it is my opinion that Miura teaches or suggests that the noble metals are distributed in the particle as an eggshell such that a higher concentration of the noble metals is present in the outer region as compared to the concentration of the noble metals in the center of the particle.

(ii) Claim 3

[3] The combustion promoter according to claim 1, comprising a plurality of microsphere sized porous particles comprising alumina.

90. Miura discloses that its combustion promoter includes a plurality of microsphere sized porous particles comprising alumina. For example, Miura discloses that the “metal oxide support may be formed of various materials but, in order to obtain a large surface area, *alumina* (Al_2O_3) has been heretofore generally used.” Miura, [0003]. Miura discloses “a metal oxide particle comprising a core

part relatively rich in a component originated in the population of first colloid particles” wherein the “population of first colloid particles” may be alumina particles and, more specifically, may be *γ-alumina* particles. Miura, [0014], [0015], [0023]-[0026]. Further, Miura discloses that the “metal oxide support may be formed of various materials but, in order to obtain a large surface area, *alumina* (Al₂O₃) has been heretofore generally used.” *Id.*, [0003].

91. Miura’s disclosure is also aligned with the applicant’s admissions in the ’864 patent that CO to CO₂ combustion promoters are well known in the art and “are commonly made from impregnation of Group VIII noble metal or metals, commonly platinum and/or palladium, onto a porous alumina and/or other substrate microspheres of average particle size 60 to 90 microns.” ‘864 patent, 1:62-2:3.

(iii) Claim 6

[6] The combustion promoter according to claim 1, wherein the microsphere sized porous particles collectively have an average (D50) size of between 60 and 90 microns as measured by laser diffraction.

92. Miura discloses that “a metal oxide particle having any particle diameter and having a structure comprising a core part and a surface layer can be obtained,” and discloses a range of average particle diameters of the metal oxide particles as “less than 10 μm, less than 5 μm, less than 1 μm, less than 500 nm, less than 200 nm, less than 100 nm or less than 50 nm,” and teaches the benefits of

small particle size. *Id.*, [0015], [0068]. To the extent Miura does not explicitly disclose an average size of between 60 and 90 microns, the applicant admitted that CO to CO₂ combustion promoters were well known in the art and were “commonly made from impregnation of Group VIII noble metal or metals, commonly platinum and/or palladium, onto a porous alumina and/or other substrate *microspheres of average particle size 60 to 90 microns.*” ’864 patent, 1:62-2:3. Therefore, a POSITA would have known that particles having an average diameter size of less than 1mm, and an average size of between 60 and 90 microns, were known for use in CO to CO₂ combustion promoters like those disclosed in Miura. Likewise, the applicant admitted during prosecution that a POSITA would be familiar with “microspheres” in the context of CO to CO₂ combustion promoters as “spherical particles as small as 1 micron in diameter and as large as 1,000 microns (1 mm).” ’864 File History, 94 (internal citations omitted). Further, a POSITA would have understood that laser diffraction is a common and well-known technique for measuring particle size.

93. Thus, a POSITA would have recognized that the microsphere-sized particles taught by Miura comprising a CO to CO₂ combustion promoter may have an average particle diameter size of between 60 and 90 microns and would be motivated to apply those particles to the “eggshell” structure taught by Miura. Indeed, the ’864 Patent recognizes that “impregnation of Group VIII noble metal

or metals, commonly platinum and/or palladium, onto a porous alumina and/or other substrate *microspheres of average particle size 60 to 90 microns* . . . results in uniform distribution of the Group VIII noble metal throughout the internal and external surfaces of the porous microsphere.” ’864 patent, 1:62-2:3. A POSITA would be motivated to combine the AAPA disclosure with Miura because Miura likewise recognizes that a substantially uniform metal oxide particle does not always yield the best result. Miura, FIG 2, [0009], [0068]. Each of the ’864 patent and Miura teaches the “eggshell” structure having a core part and surface layer, as described in [1b], is preferred to a uniform structure and also teaches the benefits of small particle diameter. Miura, FIG 2, [0009], [0068]. Thus, a POSITA would have been motivated to combine the “eggshell structure,” as described by Miura, with the particle size known in the art.

(iv) Claim 7

[7] The combustion promoter according to claim 1, wherein the microsphere sized porous particles are gamma or theta alumina particles.

94. Miura discloses its microsphere sized particles are gamma or theta alumina particles. For example, Miura discloses “three-way catalysts where a noble metal such as platinum (Pt), rhodium (Rh) and palladium (Pd) is supported *on a porous metal oxide support such as γ -alumina*,” and that γ -alumina was a known porous metal oxide support used in purifying catalysts. Miura, [0002].

(v) Claim 12

[12] The combustion promoter according to claim 1, wherein the one or more Group VIII noble metals comprises one or more of platinum, palladium, iridium, ruthenium, and rhodium.

95. Miura discloses the one or more Group VIII noble metals comprises one or more of platinum, palladium, iridium, ruthenium, and rhodium. For example, Miura discloses “three-way catalysts where a noble metal such as *platinum (Pt), rhodium (Rh) and palladium (Pd)* is supported on a porous metal oxide support such as γ -alumina.” Miura, [0002]. Further, Miura discloses an embodiment wherein a “noble metal such as *platinum, rhodium and palladium* is supported on the metal oxide particle” and “[t]he noble metal to be supported is preferably at least one selected from the group consisting of *Pt, Pd, Rh, Ir* and Au.” *Id.*, [0048], [0068], [0072].

(vi) Claim 13

[13] The combustion promoter according to claim 12, wherein the one or more Group VIII noble metals comprises platinum and palladium.

96. Miura discloses the one or more Group VIII noble metals comprises platinum and palladium. For example, Miura discloses, as known in the art, “three-way catalysts where a noble metal such as *platinum (Pt)*, rhodium (Rh) *and palladium (Pd)* is supported on a porous metal oxide support such as γ -alumina.” Miura, [0002]. Further, Miura discloses an embodiment wherein a “noble metal such as *platinum*, rhodium *and palladium* is supported on the metal oxide

particle” and “[t]he noble metal to be supported is preferably at least one selected from the group consisting of ***Pt***, ***Pd***, Rh, Ir and Au.” *Id.*, [0048], [0072].

(vii) **Claim 14**

[14] The combustion promoter according to claim 12, wherein the one or more Group VIII noble metals comprises platinum.

97. Miura discloses the one or more Group VIII noble metals comprises platinum. For example, Miura discloses, as known in the art, a “three-way catalysts where a noble metal such as ***platinum (Pt)***, rhodium (Rh) and palladium (Pd) is supported on a porous metal oxide support such as γ -alumina.” Miura, [0002]. Further, Miura discloses an embodiment wherein a “noble metal such as ***platinum***, rhodium and palladium is supported on the metal oxide particle” and “[t]he noble metal to be supported is preferably at least one selected from the group consisting of ***Pt***, Pd, Rh, Ir and Au.” *Id.*, [0048], [0072].

(viii) **Claim 15**

[15] The combustion promoter according to claim 12, wherein the one or more Group VIII noble metals comprises palladium.

98. Miura discloses the one or more Group VIII noble metals comprises palladium. For example, Miura discloses, as known in the art, a “three-way catalysts where a noble metal such as platinum (Pt), rhodium (Rh) and ***palladium (Pd)*** is supported on a porous metal oxide support such as γ -alumina.” Miura, [0002]. Further, Miura discloses an embodiment wherein a “noble metal such as platinum, rhodium and ***palladium*** is supported on the metal oxide particle” and

“[t]he noble metal to be supported is preferably at least one selected from the group consisting of Pt, *Pd*, Rh, Ir and Au.” *Id.*, [0048], [0072].

(ix) Claim 16

[16] The combustion promoter according to claim 1, wherein the microsphere sized porous particles further comprise at least one of cerium oxide and copper oxide.

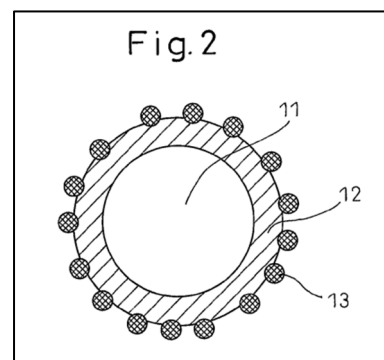
99. Miura discloses the microsphere sized porous particles further comprise at least one of cerium oxide and copper oxide. For example, Miura discloses “a *metal oxide particle* comprising a core part relatively rich in a component originated in the population of first colloid particles and a surface layer relatively rich in a component originated in the population of second colloid particles can be obtained.” Miura, [0014]. Miura discloses the surface layer is relatively rich in particles “selected from the group consisting of alumina, *ceria*, zirconia and titania colloid particles group,” and may be ceria. *Id.*, [0023]-[0026]. Miura notes that the term “relatively rich” to describe the composition of the core part and surface layer is used with respect to the molar fraction based on the total molar number of metals in each of the core part and the surface layer. *Id.*, [0016]. Miura further discloses a surface layer (12) of particulate support comprising *cerium oxide* (CeO_2) which covers an entire core part (11) formed of ZrO_2 , and a noble metal (13), such as platinum, supported on the particulate support. *Id.*, FIG 2, [0068].

(x) Claim 17

[17] The combustion promoter according to claim 16, wherein the at least one of cerium oxide and copper oxide is distributed in the microsphere sized porous particle as an eggshell such that a higher concentration of the at least one of cerium oxide and copper oxide is present in the outer region of the microsphere sized porous particle as compared to the concentration of the at least one of cerium oxide and copper oxide in the centre of the microsphere sized porous particle.

100. Miura discloses wherein the at least one of cerium oxide and copper oxide is distributed in the microsphere sized porous particle as an eggshell such that a higher concentration of the at least one of cerium oxide and copper oxide is present in the outer region of the microsphere sized porous particle as compared to the concentration of the at least one of cerium oxide and copper oxide in the centre of the microsphere sized porous particle. For example, as shown above, Miura discloses an eggshell catalyst wherein “a metal oxide particle comprising a core part relatively rich in a component originated in the population of first colloid particles and a surface layer relatively rich in a component originated in the population of second colloid particles can be obtained.” Miura, [0014]. Miura discloses the surface layer (i.e., outer region) is relatively rich in particles “selected from the group consisting of alumina, ceria, zirconia and titania colloid particles group,” and may be ceria. *Id.*, [0023]-[0026]. Miura further discloses than a

“noble metal such as platinum, rhodium and palladium is supported on . . . the surface layer” wherein platinum is more the most preferable. *Id.* [0048], [0072]. Miura discloses that the surface layer 12 (i.e., outer region) is relatively rich in particles “selected from the group



consisting of alumina, ceria, zirconia and titania colloid particles,” and may particularly be ceria (i.e., cerium oxide). Miura, [0023]-[0026], Fig. 2; Miura depicts its resulting structure—referred to in the art as an “eggshell”—in Fig. 2, depicting a surface layer (12) of particulate support comprising CeO_2 which covers an entire core part (11) formed of ZrO_2 or alternatively, alumina, and a noble metal (13), such as platinum, supported on the particulate support. *Id.*, FIG 2, [0068], [0023]-[0026]. In this manner, as shown and described with respect to Fig. 2, Miura teaches or suggests that the cerium oxide is distributed in the particle as an eggshell such that a higher concentration of the cerium oxide is present in the surface layer 12 (i.e., the outer region) as compared to the concentration of the cerium oxide in the center of the particle. *Id.*, FIG 2, [0068], [0023]-[0026].

(xi) Claim 18

[18pre] The combustion promoter according to claim 1, obtained by a process comprising the following steps:

101. To the extent the preamble is deemed to be limiting, Miura-AAPA renders obvious [18pre] for the same reasons as discussed with respect to [1pre].

For example, Miura discloses “an exhaust gas purifying catalyst and a process for producing a metal oxide particle comprising multiple species of metal oxides and capable of satisfactorily exerting the properties of respective metal oxides.” Miura, Abstract. Miura further discloses that the disclosed exhaust purifying catalyst is capable of oxidizing CO (i.e., converting CO to CO₂). *Id.*, [0002]. Miura additionally discloses a range of average particle diameters of the metal oxide particles as, “less than 10 μm, less than 5 μm, less than 1 μm, less than 500 nm, less than 200 nm, less than 100 nm or less than 50 nm,” and teaches the benefits of small particle size. *Id.*, [0015], [0068]. Therefore, Miura discloses a CO to CO₂ combustion promoter including microsphere sized particles having an average diameter size of less than 1mm. While Miura discloses particles having an average diameter size of less than 1mm, Miura discloses particle sizes ranging from 10 μm and smaller. Miura thereby discloses particle sizes on a different scale of magnitude from the upper range of the preamble of the claim. Regardless, a POSITA would have been familiar with particle sizes in the 1mm and tens of microns range used in combination with combustion promoters. Indeed, the applicant of the '864 Patent admitted that microsphere sized particles are well known in the art and were commonly used as CO to CO₂ combustion promoters. *See, e.g.*, '864 patent, 1:62-66 (“Such CO to CO₂ promoters are ***commonly made*** from impregnation of Group VIII noble metal or metals, commonly platinum

and/or palladium, onto a porous alumina and/or other substrate *microspheres of average particle size 60 to 90 microns.*").

102. To the extent Miura does not explicitly disclose the preamble, the applicant admitted that CO to CO₂ combustion promoters were well known in the art and “are commonly made from impregnation of Group VIII noble metal or metals, commonly platinum and/or palladium, onto a porous alumina and/or other substrate microspheres of average particle size 60 to 90 microns.” ’864 patent, 1:62-2:3. Thus, particles having an average diameter size of less than 1mm, like those disclosed in Miura, were known for use in CO to CO₂ combustion promoters. Likewise, the applicant admitted during prosecution that a POSITA would be familiar with “microspheres” in the context of CO to CO₂ combustion promoters as “*spherical particles as small as 1 micron in diameter and as large as 1,000 microns (1 mm).*” ’864 File History, 94 (internal citations omitted). A POSITA would thereby have been motivated to use particles less than 1mm in diameter in a CO to CO₂ combustion promoter.

[18a] introducing a medium in the pores of microsphere sized porous particles having a diameter of less than 1 mm to obtain microsphere sized porous particles with filled pores; and

103. Miura-AAPA renders obvious introducing a medium in the pores of microsphere sized porous particles having a diameter of less than 1 mm to obtain microsphere sized porous particles with filled pores for the same reasons as

discussed with respect to [1pre]. For example, Miura discloses “an exhaust gas purifying catalyst and a process for producing a metal oxide particle comprising multiple species of metal oxides and capable of satisfactorily exerting the properties of respective metal oxides.” Miura, Abstract. Miura additionally discloses a range of average particle diameters of the metal oxide particles as, “less than 10 μm , less than 5 μm , less than 1 μm , less than 500 nm, less than 200 nm, less than 100 nm or less than 50 nm,” and teaches the benefits of small particle size. *Id.*, [0015], [0068]. Therefore, Miura discloses particles having an average diameter size of less than 1mm. Miura, [0015], [0068]. Miura further discloses a surface layer of particulate support covering a core part and a noble metal supported on the surface layer of particulate support. Miura, FIG 2, [0068]. Miura discloses that the “noble metal may be loaded on the metal oxide particle by any known method, for example, by a method of impregnating metal oxide particles with a solution containing a salt and/or a complex salt of noble metal, and drying and then firing it.” *Id.*, [0049]. Miura further discloses that the “noble metal can be supported by dispersing the particulate support in distilled water and adding a noble metal solution, followed by stirring, drying and further firing.” *Id.*, [0072]. In one example implementation, Miura further discloses that the particulate supports were “dispersed in distilled water” to which “an *aqueous dinitrodiamine platinum solution* (Pt content: 4.4% by weight) was added thereto.” *Id.*, [0101].

104. As described above, a POSITA would combine Miura with the AAPA to apply the teachings of Miura to the full range of microsphere sized pores. The applicant admitted that CO to CO₂ combustion promoters are well known in the art and “commonly made from impregnation of Group VIII noble metal or metals, commonly platinum and/or palladium, onto a porous alumina and/or other substrate *microspheres of average particle size 60 to 90 microns*,” ’864 patent, 1:62-2:3, and therefore particles having an average diameter size of less than 1mm was known for use in CO to CO₂ combustion promoters. Likewise, the applicant admitted during prosecution that a POSITA would be familiar with “microspheres” in the context of CO to CO₂ combustion promoters as “spherical particles as small as 1 micron in diameter and as large as 1,000 microns (1 mm).” ’864 File History, 94 (internal citations omitted). Thus, a POSITA would have been motivated to use the particles less than 1mm in a CO to CO₂ combustion promoter.

[18b] contacting the microsphere sized porous particles with filled pores with an aqueous salt solution of the one or more Group VIII noble metals,

105. Miura discloses contacting the microsphere sized porous particles with filled pores with an aqueous salt solution of the one or more Group VIII noble metals. For instance, Miura discloses that the “noble metal may be loaded on the metal oxide particle by any known method, for example, by a method of impregnating metal oxide particles with a solution containing a salt and/or a complex salt of noble metal, and drying and then firing it.” *Id.*, [0049]. Miura also

discloses a surface layer of particulate support and the noble metal supported on the particulate support, wherein the “noble metal can be supported by dispersing the particulate support in distilled water and adding a noble metal solution.”

Miura, FIG 2, [0068], [0072]; *see also id.*, [0049]. In another example, Miura discloses that the particulate supports were “dispersed in distilled water” to which “an *aqueous dinitrodiamine platinum solution* (Pt content: 4.4% by weight) was added thereto.” *Id.*, [0101]. Miura therefore discloses or at least suggests to a POSITA that the obtained particulate supports are first dispersed in distilled water such that the particulate supports are filled with water, and then contacted with an aqueous salt solution containing a noble metal, such as platinum, stirred, for one hour, and then dried and fired to obtain the disclosed catalyst. *Id.*, [0101].

[18c] wherein the one or more Group VIII noble metals deposits at a higher content in the outer region of the microsphere sized porous particles with filled pores as compared to the content of the one or more Group VIII noble metals in the centre of the microsphere sized porous particles with filled pores, thereby obtaining eggshell particles.

106. Miura discloses that the one or more Group VIII noble metals deposits at a higher content in the outer region of the microsphere sized porous particles with filled pores as compared to the content of the one or more Group VIII noble metals in the centre of the microsphere sized porous particles with filled pores, thereby obtaining eggshell particles for the same reasons as discussed with respect to [1b]. For example, Miura discloses an eggshell catalyst having “a metal oxide

particle comprising a core part relatively rich in a component originated in the population of first colloid particles and a surface layer relatively rich in a component originated in the population of second colloid particles can be obtained.” Miura, [0014]. Miura therefore discloses the surface layer (i.e., outer region) is relatively rich in particles “selected from the group consisting of alumina, ceria, zirconia and titania colloid particles group,” and may be ceria. *Id.*, [0023]-[0026]. Miura further discloses that a “noble metal such as platinum, rhodium and palladium is supported on . . . the surface layer” wherein platinum is the most preferable. *Id.* [0048], [0072]. Miura depicts this structure—referred to in the art as an “eggshell”— in FIG. 2, depicting a surface layer (12) of particulate support comprising CeO₂ which covers an entire core part (11) formed of ZrO₂, and a noble metal (13), such as platinum, supported on the particulate support. *Id.*, FIG 2, [0068].

(xii) Claim 19

[19] The combustion promoter of claim 18, the process further comprising a step: (c) at least one of drying and calcining the eggshell particles.

107. Miura discloses claim 19. Miura discloses a surface layer of particulate support and a noble metal supported on the particulate support, wherein the “noble metal can be supported by dispersing the particulate support in distilled water and adding a noble metal solution, *followed by stirring, drying and further firing.*” Miura, FIG 2, [0068], [0072]; *see also id.*, [0049]. Miura further discloses

that the particulate supports were dispersed in distilled water and then, the “water content was removed by drying at 120°C. for 24 hours and the residue was fired at 500°C. for 2 hours.” *Id.*, [0101].

(xiii) Claim 21

[21] The combustion promoter according to claim 18, wherein the medium in step (a) is water.

108. Miura discloses claim 21. Miura discloses a surface layer of particulate support and a noble metal supported on the particulate support, wherein the “noble metal can be supported by dispersing the particulate support in *distilled water* and adding a noble metal solution.” Miura, FIG 2, [0068], [0072]; *see also id.*, [0049]. Miura further discloses that the particulate supports were “dispersed in *distilled water*” to which “an aqueous dinitrodiamine platinum solution (Pt content: 4.4% by weight) was added” and “and the resulting dispersion was stirred for 1 hour.” Miura, [0101].

**I. [GROUND 1A] – CLAIM 9 IS OBVIOUS OVER MIURA
IN VIEW OF AAPA AND IN FURTHER VIEW OF
VAUGHN 290**

109. It is my opinion that a POSITA would have found claim 9 to be obvious over Miura and AAPA and in further view of Vaughn 290, as I discuss in the following sections.

1. Overview of Vaughn 290

110. Vaughn 290 is directed to “a catalyst which contains molecular sieve-containing attrition particles and virgin molecular sieve, the attrition particles having been recycled from a catalyst manufacture process or from a reaction system.” Vaughn 290, 1:7-13. Vaughn 290 further teaches that the disclosed catalyst may be used in a variety of catalytic reaction processes such that the recycled catalyst particles can be used to form a catalytic composition. *Id.*, Abstract, 2:43-45. A POSITA would have recognized the variety of catalytic reaction processes as including a CO to CO₂ combustion promoter. Vaughn 290 teaches the benefits of the recycled catalyst composition as “beneficial in minimizing waste, thereby reducing problems relating to both environmental and economic constraints.” *Id.*, Abstract.

2. Combination of Miura, AAPA, and Vaughn 290

111. It is my opinion that a POSITA would have been motivated to use the equilibrium or spent catalyst particles, such as those described by Vaughn 290, to the eggshell catalyst structure disclosed in Miura for at least the reasons I discuss below.

112. As I described above, Miura discloses “an exhaust gas purifying catalyst and process for producing a metal oxide particle” wherein the particle comprises “a core part relatively rich in a component originated in a population of

first colloid particles and a surface layer relatively rich in a component originated in the population of second collide particles.” Miura, Abstract, [0014]. Vaughn 290, similar to Miura and the AAPA, discloses a catalyst which contains molecular sieve-containing attrition particles and virgin molecular sieve, the attrition particles having been recycled from a catalyst manufacture process or from a reaction system.” Vaughn 290, 1:7-13. Vaughn 290 further teaches that the disclosed catalyst may be used in a variety of catalytic reaction processes, such that the recycled catalyst particles can be used to form a catalytic composition. *Id.*, Abstract, 2:43-45. A POSITA would have recognized the variety of catalytic reaction processes as including a CO to CO₂ combustion promoter. In addition, Vaughn 290 discloses **recycled** particles that “are actually molecular sieve-containing catalyst particles that have be [sic] used in a functioning manufacture or reaction system, and have been reduced in size due to attrition.” Vaughn 290, 9:55-65. Vaughn 290 discloses that the “catalyst fines are recovered from the manufacture or reaction system and are recycled back into the catalyst manufacturing scheme. The catalyst fines, therefore, are incorporated into the finished catalyst particles.” Vaughn 290, 9:55-65, 16:26-35. While Miura does not explicitly disclose an equilibrium or spent catalyst, a POSITA would understand that “the recovery and use of the attrition particles in [a] catalyst is

beneficial in minimizing waste, thereby reducing problems relating to both environmental and economic constraints.” Vaughn 290, Abstract.

113. By incorporating the recycling teachings of Vaughn 290 into Miura, a POSITA would have recognized the efficiencies and benefits of recycling catalyst material in combination with Miura’s eggshell catalyst. Indeed, Vaughn 290 teaches that “the recovery and use of the attrition particles in [a] catalyst is beneficial in minimizing waste, thereby reducing problems relating to both environmental and economic constraints.” Vaughn 290, Abstract. Miura discloses that a “noble metal [13, shown in Fig. 2] such as platinum, rhodium and palladium is supported on the metal oxide particle. . . [and] mainly on the surface layer [12].” Miura, [0048], [0072], Fig. 2. A POSITA would recognize the expense of the noble metals disclosed in Miura and appreciate the cost-saving efficiencies that Miura teaches by depositing the noble metal on the surface of the particle, rather than uniformly distributed throughout the particles. This cost-saving measure of Miura would motivate a POSITA to apply additional efficiencies to the preparation of the catalyst particles, namely the recycling process disclosed by Vaughn 290.

114. A POSITA would have been further prompted to pursue the efficiencies of Vaughn 290 as doing so is merely the application of known techniques (*e.g.*, recycling combustion promoter particles) to a known structure (*e.g.*, the combustion promoter particles) to yield predictable results (*e.g.*,

minimizing waste). And a POSITA would have expected success in the Miura-Vaughn 290 combination given that each already describes catalyst for use in a variety of catalytic reaction processes, including the well-known CO to CO₂ combustion promotion process, and the inherent cost-saving of both Miura and Vaughn 290. *See* Miura, Abstract, [0014]; Vaughn 290, Abstract, 2:43-45.

3. Analysis

(i) Claim 9

[9] The combustion promoter according to claim 1, wherein the microsphere sized porous particles are an equilibrium or spent catalyst as obtained from a fluidized catalytic cracking (FCC) process.

115. Miura-AAPA-Vaughn 290 renders obvious the microsphere sized porous particles are an equilibrium or spent catalyst as obtained from a fluidized catalytic cracking (FCC) process. As discussed above, Miura-AAPA renders obvious claim 1. Vaughn 290 discloses recycled particles that “are actually molecular sieve-containing catalyst particles that have be used in a functioning manufacture or reaction system, and have been reduced in size due to attrition.” Vaughn 290, 9:55-65. Vaughn 290 further discloses that these “catalyst fines are recovered from the manufacture or reaction system and are recycled back into the catalyst manufacturing scheme. The catalyst fines, therefore, are incorporated into the finished catalyst particles.” *Id.*; *see also id.*, 16:26-35. The recycled catalyst disclosed in Vaughn 290 is a spent catalyst as described by the ’864 Patent. The ’864 patent describes an equilibrium or spent catalyst as “obtained from a FCC

process wherein fresh FCC catalyst has deactivated by some degree” such that the “catalyst particles may thus find a suitable second use as a CO to CO₂ combustion promoter.” ’864 patent, 4:47-53. Thus, Vaughn 290 teaches recovery and recycling of spent catalyst back to a catalyst manufacturing process such that the spent catalyst may be incorporated into the manufacture of additional catalyst particles, such as those disclosed by Miura and AAPA. Vaughn 290, 9:55-65, 16:26-35.

J. [GROUND 1B] – CLAIMS 10 & 11 ARE OBVIOUS OVER MIURA IN VIEW OF AAPA AND IN FURTHER VIEW OF PETERS OR, ALTERNATIVELY, VAUGHN 516

116. It is my opinion that a POSITA would have found claims 10 and 11 to be obvious over Miura and AAPA and in further view of Peters or, alternatively, Vaughn 516, as I discuss in the following sections.

1. Overview of Peters

117. Peters is directed to “compositions suitable for use in FCC processes which are capable of promoting CO combustion while avoiding significant NO_x formation.” Peters, 1:49-60. Peters discloses combustion particles comprising “a component containing (i) an acidic oxide support, (ii) an alkali metal and/or alkaline earth metal or mixtures thereof, (iii) a transition metal oxide having oxygen storage capability, and (iv) palladium.” *Id.* Peters further discloses that

the acidic oxide support is preferably silica alumina and the preferred oxygen storage oxide is ceria. *Id.*

2. Combination of Miura and Peters

118. It is my opinion that a POSITA would have recognized the attrition value of catalyst particles, such as those described by Peters, to the eggshell catalyst particles disclosed in Miura and would have been motivated to combine the two references for at least the reasons I discuss below.

119. As described above, Miura discloses “an exhaust gas purifying catalyst and process for producing a metal oxide particle” wherein the particle comprises “a core part relatively rich in a component originated in a population of first colloid particles and a surface layer relatively rich in a component originated in the population of second collide particles.” Miura, Abstract, [0014]. However, Miura does not expressly disclose an attrition index of the metal oxide particles, though a POSITA would understand that catalyst material should be durable and attrition-resistant and therefore a low attrition index is desirable, while reducing NO_x emissions.

120. Peters, similar to Miura, discloses “compositions suitable for use in FCC processes which are capable of promoting CO combustion while avoiding significant NO_x formation.” Peters, 1:49-60. Miura and Peters teach the use of similar components of the combustion promoter, namely, the use of ceria as the

preferred oxide component as the outer layer (most susceptible to attrition) of the eggshell structure disclosed by Miura. *See* Miura, [0068]; Peters, 1:49-60. And while Miura is silent as to the attrition index, Peters explicitly identifies the attrition index value of the combustion promoter composition. Peters, 3:9-20.

121. A POSITA would have understood that Miura teaches the use of ceria as the outer portion of the particle and, thus, the surface layer most susceptible to attrition. For example, Miura discloses that the surface layer 12 (i.e., outer region) is relatively rich in particles “selected from the group consisting of alumina, ceria, zirconia and titania colloid particles,” and may particularly be ceria (i.e., cerium oxide). Miura, [0023]-[0026], Fig. 2. Miura depicts its resulting structure—referred to in the art as an “eggshell”—in Fig. 2, depicting a surface layer (12) of particulate support comprising CeO_2 which covers an entire core part (11) formed of ZrO_2 or alternatively, alumina, and a noble metal (13), such as platinum, supported on the particulate support. *Id.*, FIG 2, [0068], [0023]-[0026]. In this manner, as shown and described with respect to Fig. 2, Miura teaches or suggests that the cerium oxide is distributed in the particle as an eggshell such that a higher concentration of the cerium oxide is present in the surface layer 12 (i.e., the outer region) as compared to the concentration of the cerium oxide in the center of the particle. *Id.*, FIG 2, [0068], [0023]-[0026]. A POSITA would thereby have understood the disclosure of Miura would have similar attrition properties to the

value disclosed by Peters where Peters likewise teaches the use of ceria as a component of the catalyst particle.

122. By incorporating the specific attrition index teachings of Peters to Miura, a POSITA would have recognized that the attrition index value of Miura, using the same cerium oxide as the outer layer of the combustion particles, would have been similar or equivalent to the values disclosed in Peters. A POSITA would have been further prompted to pursue the optimal attrition index of the combustion promoter particles, as doing so is merely the application of known techniques (*e.g.*, standard attrition measurement) to a known structure (*e.g.*, the combustion promoter particles) to yield predictable results (*e.g.*, improved attrition properties). '864 patent, 6:53-63. A POSITA would have had a reasonable expectation of success in the Miura-Peters combination given that both already describe using cerium oxide as the preferred metal oxide component of the combustion promoter. *See* Miura, [0068]; Peters, 1:49-60.

3. Overview of Vaughn 516

123. Vaughn 516 is directed to processes for removing undesirably sized catalyst particles from a catalyst synthesis system; in particular, Vaughn 516 discloses a molecular sieve to obtain a slurry of optimally-sized catalyst particles. Vaughn 516, Abstract. Vaughn 516 teaches that the benefit of the disclosed

processes is to obtain a formulated catalyst mixture with desirable catalytic activity characteristics for use in a reaction system. *Id.*

4. Combination of Miura and Vaughn 516

124. It is my opinion that a POSITA would have recognized the attrition value of catalyst particles, such as those described by Vaughn 516, to the eggshell catalyst particles disclosed in Miura and would have been motivated to combine the two references for at least the reasons I discuss below.

125. As described above, Miura discloses “an exhaust gas purifying catalyst and process for producing a metal oxide particle” wherein the particle comprises “a core part relatively rich in a component originated in a population of first colloid particles and a surface layer relatively rich in a component originated in the population of second collide particles.” Miura, Abstract, [0014]. Therefore, a POSITA would have recognized that Miura teaches that the core part of the particle is does not contain or has a low concentration of the noble metal component, specifically platinum and palladium, that are present on the surface of the particle. *Id.*, [0048], [0072], Fig. 2. However, Miura does not expressly disclose an attrition index of the metal oxide particles, though a POSITA would understand that catalyst material should be durable and attrition-resistant and therefore a low attrition index is desirable, while reducing NO_x emissions.

126. Vaughn 516 is directed to processes for removing undesirably sized catalyst particles from a catalyst synthesis system; in particular, Vaughn 516 discloses a molecular sieve to obtain a slurry of optimally-sized catalyst particles. Vaughn 516, Abstract. Vaughn 516 teaches that the benefit of the disclosed processes is to obtain a formulated catalyst mixture with desirable catalytic activity characteristics for use in a reaction system. *Id.* Vaughn 516, similar to Miura, discloses processes to obtain catalyst particles with optimal properties, *e.g.*, size. *Id.*, Abstract. In particular, Vaughn 516 teaches an embodiment wherein the particle size of the molecular sieve catalyst particles range from 5 microns to 10 microns, which overlap with the particle size disclosed by Miura. Vaughn 516, [0011], [0014], [0075]; Miura, [0015], [0068]. Vaughn 516, similar to Miura, teaches the use of similar components of the catalyst particles, namely, the matrix or support material contains alumina. *See* Miura, [0003], [0014], [0023]-[0026]; Vaughn 516, [0085]. Likewise, Vaughn 516, similar to Miura, teaches the use of Group VIII metals, including platinum and palladium, as reactive components of the catalytic particle. Vaughn 516, [0108], [0164]; Miura, [[0048], [0072], Fig. 2]. And, while Miura is silent as to the attrition index, Vaughn 516 explicitly identifies the attrition index value of the combustion promoter composition. Vaughn 516, [0131].

127. A POSITA would have understood that Miura teaches the an “eggshell” structure in Fig. 2, depicting a surface layer (12) of particulate support comprising CeO_2 which covers an entire core part (11) formed of ZrO_2 or alternatively, alumina, and a noble metal (13), such as platinum, supported on the particulate support. *Id.*, FIG 2, [0068], [0023]-[0026]. In this manner, as shown and described with respect to Fig. 2, Miura teaches or suggests a low concentration of the noble metal in the core of the eggshell. *Id.*, FIG 2, [0068], [0023]-[0026]. Likewise, Vaughn 516, similar to Miura, teaches the use of Group VIII metals, including platinum and palladium, such that the concentration of the Group VIII metal is low in the support material. Vaughn 516, [0108], [0164]; Miura, [0048], [0072], Fig. 2]. Vaughn 516 specifically teaches that this design choice is effective in reducing overall catalyst cost and “increasing catalyst strength such as crush strength and attrition resistance.” Vaughn 516, [0106]. A POSITA would thereby have understood the disclosure of Miura would have similar attrition properties to the value disclosed by Vaughn 516 where Vaughn 516 likewise teaches catalytic components with similar distributions within the catalyst particle.

128. By combining the specific attrition index teachings of Vaughn 516 with Miura, a POSITA would have recognized that the attrition index value of Miura, using the same catalytic components with similar distributions within the combustion particles, would have been similar or equivalent to the values disclosed

in Vaughn 516. A POSITA further would have been led to pursue the optimal attrition index of the combustion promoter particles because doing so is merely the application of known techniques (*e.g.*, standard attrition measurement) to a known structure (*e.g.*, the combustion promoter particles) to yield predictable results (*e.g.*, improved attrition properties). '864 patent, 6:53-63 (“The skilled person will be able to find the optimal Attrition Index for the CO to CO₂ combustion promoter depending for example on the desired residence time and the influence of the FCC unit itself to the attrition of the FCC catalyst inventory. This process of finding the optimal Attrition Index may for example be an empirical iteration, where the attrition resistance of the additive is lowered (attrition increased) until the NO_x emissions are lowered, and further reduction in the attrition resistance requires an increase in the addition rate of the combustion promoter.”). And a POSITA would have had a reasonable expectation of success in the Miura-Vaughn 516 combination given that both already describe using platinum or palladium as the catalytic component of the combustion promoter with similar distribution. *See* Miura, [0068]; Vaughn 516, [0086].

5. Analysis

(i) Claim 10

[10] The combustion promoter according to claim 1, wherein the attrition index as measured according to ASTM D-5757 of the CO to CO₂ combustion promoter for a sieve fraction of combustion promoter particles of between 40 and 105 microns is between 5 and 25.

129. Miura-AAPA-Peters or, alternatively, Miura-AAPA-Vaughn 516 renders obvious claim 10. As discussed above, Miura-APPA renders obvious claim 1. Further, Peters or Vaughn 516 in combination with Miura-AAPA renders obvious a sieve fraction of combustion promoter particles between 40 and 105 microns having an attrition index between 5 and 25.

130. Peters discloses a combustion promoter for use in FCC catalytic processes such that when the promoter is used as an additive particulate, the *average particle size is 20-200 microns* and the attrition value of the additive particles measured by the *Davison attrition index (DI) is “about 0-45, more preferable about 0-15.”* Peters, 3:9-20. A POSITA would have recognized that the ASTM D-5757 value disclosed in the '864 Patent is comparable to the DI value used in Peters. ASTM Standard. Namely, the basis for the ASTM standard is an air-jet attrition test, which was well-known in the art as a model to analyze data obtained using an air-jet apparatus for measuring attrition resistance. *See* Wu. Similarly, the Davison attrition index is described as a jet-cup attrition test method, wherein a POSITA would have appreciated that this method has the advantage that less catalyst sample and was able to assess the attrition resistance of a powder. *See* Cocco. POSITA would have appreciated that the ASTM D-5757 standard is a procedure to prepare a sample of catalyst material and measure the percent loss of the mass of the material over a period of time; likewise, the DI procedure disclosed

by Peters employs a similar preparation procedure to calculate the same value, attrition, as loss of the catalyst material over a period of time.

131. Moreover, as the '864 Patent recognizes, the “skilled person will be able to find the optimal Attrition Index for the CO to CO₂ combustion promoter depending for example on the desired residence time and the influence of the FCC unit itself to the attrition of the FCC catalyst inventory.” '864 patent, 6:53-63. Further, the '864 Patent acknowledges that “[t]his process of finding the optimal Attrition Index may for example be an empirical iteration.” *Id.* Thus, a POSITA would have recognized that Peters teaches an overlap of the claimed average particle size (40-105 microns) and claimed attrition value (10-20 or, preferably, 10-15) and therefore renders obvious claim 10.

132. Vaughn 516 discloses obtaining a catalytic composition containing a molecular sieve wherein the attrition resistance of the composition is measured using an Attrition Rate Index (ARI) using a hardened steel attrition cup. Vaughn 516, [0130]. Vaughn 516 further teaches a catalyst composition of an *average particle size from 53 to 125 microns* and “*an ARI less than 15 weight percent per hour, preferably less than 10 weight percent per hour, more preferably less than 5 weight percent per hour*, and even more preferably less than 2 weight percent per hour, and most preferably less than 1 weight percent per hour.” *Id.*, [0131]. A POSITA would recognize that the ASTM D-5757 value disclosed in the '864

patent is comparable to the ARI value used in Vaughn 516. ASTM Standard. For example, a POSITA would appreciate that the ASTM D-5757 standard is a procedure to prepare a sample of catalyst material and measure the percent loss of the mass of the material over a period of time; likewise, the ARI procedure disclosed by Vaughn 516 employs a similar preparation procedure to calculate the same value, attrition, as loss of the catalyst material over a period of time.

133. Moreover, as discussed above, the '864 Patent recognizes that the “skilled person will be able to find the optimal Attrition Index for the CO to CO₂ combustion promoter” and that “[t]his process of finding the optimal Attrition Index may for example be an empirical iteration.” '864 patent, 6:53-63. Thus, a POSITA would recognize Vaughn 516 teaches an overlap of the claimed average particle size (53-105 microns) and claimed attrition value (10-15) and therefore renders obvious claim 10.

(ii) Claim 11

[11] The combustion promoter according to claim 10, wherein the attrition index of the CO to CO₂ combustion promoter for a sieve fraction of combustion promoter particles of between 40 and 105 microns is between 10 and 20.

134. Miura-AAPA-Peters or, alternatively, Miura-AAPA-Vaughn 516 renders obvious claim 11. As discussed above, Miura-APPA renders obvious claim 1. Further, as shown above, Peters or Vaughn 516 renders obvious

combustion promoter particles between 40 and 105 microns with an attrition index between 10 and 20.

135. Peters discloses combustion promoter for use in FCC catalytic processes that when the promoter is used as an additive particulate, the *average particle size is 20-200 microns* and the attrition value of the additive particles measured by the *Davison attrition index (DI) is “about 0-45, more preferable about 0-15.”* Peters, 3:9-20. A POSITA would have recognized that the ASTM D-5757 value disclosed in the '864 patent is comparable to the DI value used in Peters. ASTM Standard. Moreover, as the '864 patent recognizes, the “skilled person will be able to find the optimal Attrition Index for the CO to CO₂ combustion promoter depending for example on the desired residence time and the influence of the FCC unit itself to the attrition of the FCC catalyst inventory.” '864 patent, 6:53-63. Further, the '864 patent acknowledges that “[t]his process of finding the optimal Attrition Index may for example be an empirical iteration.” *Id.* Thus, a POSITA would recognize that Peters teaches an overlap of the claimed average particle size (40-105 microns) and claimed attrition value (5-25 or, preferably, 5-15) and therefore renders obvious claim 11.

136. Vaughn 516 discloses obtaining a catalytic composition containing a molecular sieve wherein the attrition resistance of the composition is measured using an Attrition Rate Index (ARI) using a hardened steel attrition cup. Vaughn

516, [0130]. Vaughn 516 further teaches that the catalyst composition of an *average particle size from 53 to 125 microns* and “*an ARI less than 15 weight percent per hour, preferably less than 10 weight percent per hour*, more preferably less than 5 weight percent per hour, and even more preferably less than 2 weight percent per hour, and most preferably less than 1 weight percent per hour.” *Id.*, [0131]. A POSITA would have recognized that the ASTM D-5757 value disclosed in the '864 patent is comparable to the ARI value used in Vaughn 516. ASTM Standard. Moreover, as discussed above, the '864 patent recognizes that the “skilled person will be able to find the optimal Attrition Index for the CO to CO₂ combustion promoter” and that “[t]his process of finding the optimal Attrition Index may for example be an empirical iteration.” '864 patent, 6:53-63. Thus, a POSITA would have recognized Vaughn 516 teaches an overlap of the claimed average particle size (53-105 microns) and claimed attrition value (5-15) and therefore renders obvious claim 11.

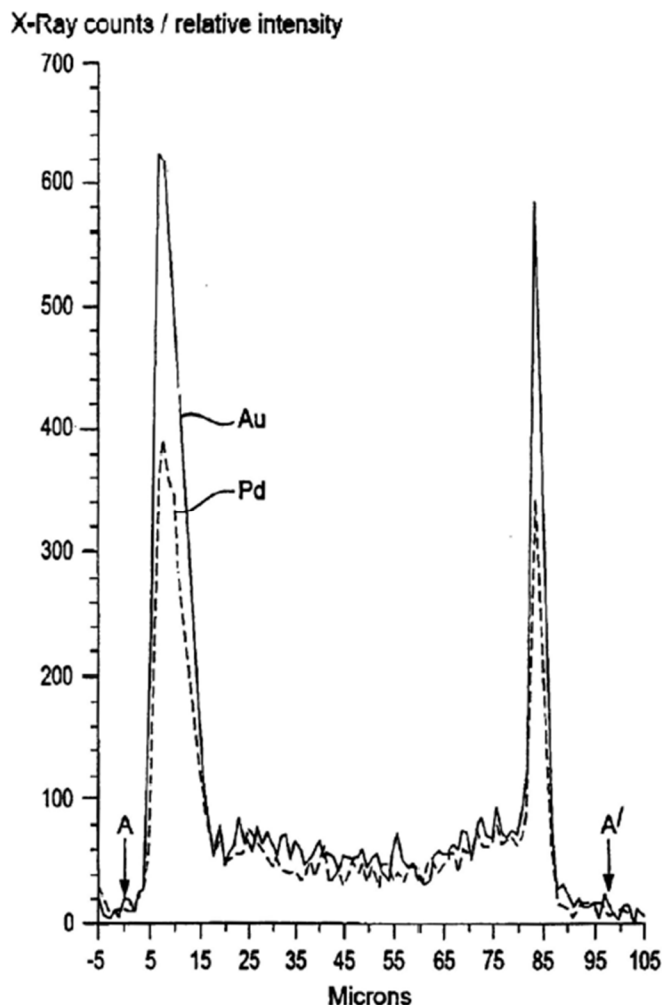
K. [GROUND 2] – CLAIMS 1-8 & 12-22 ARE OBVIOUS OVER MIURA IN VIEW OF BAKER

137. It is my opinion that a POSITA would have found claims 1-8 and 12-22 to be obvious over Miura and Baker, as I discuss in the following sections.

1. Overview of Baker

138. Baker discloses a “[p]rocess for preparing a supported metal catalyst composition comprising impregnating support particles having a mean diameter of

greater than 300 microns with a solution of least one catalytically active metal, or precursor thereof, such that the metal, or its precursor, is in a mobile state in the support particles; and drying the impregnated support particles. The mobile metal, or its precursor, in the support particles is then treated with a liquid comprising at least one reducing agent to deposit and immobilize the metal, or its precursor, in the support particles such that the metal, or its precursor, is distributed in the support particle in a layer below the surface of the support particle, the layer being between an inner and an outer region, each of the inner and outer regions having a lower concentration of the metal or precursor than the layer.” Baker, Abstract. Baker further describes that “[d]epending upon the size of the support particles, alternatively or additionally, the layer containing the catalytically active metal, or its precursor, preferably has an outer edge which is at least 3 microns and no more than 20 microns below the surface of each support particle, and is more preferably 4 to 20 microns, below the surface of each particle, and yet more preferably is 5 to 15 microns below the surface of each particle.” Baker, 2:41-58. Fig. 2 shows the distribution of the noble metals in the structure of Baker:

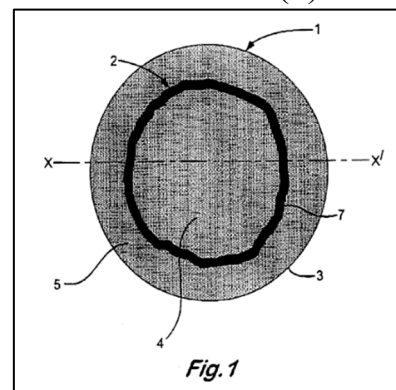


139. As can be seen from Fig. 2 of Baker and described above, the noble metals are distributed below the outer surface of the particle in such a manner that there is a higher concentration of noble metals in the outer region of Baker than the inner core. This is commensurate with the distribution of metals described and claimed in the '864 patent, especially given the fact that claims of the '864 patent recite “a higher concentration of the one or more Group VIII noble metals is present in the **outer region** of the microsphere sized porous particle as compared to the concentration of the one or more Group VIII noble metals in the **centre** of

the microsphere sized porous particle.” This is further evidenced with reference to Fig. 1 of Baker discussed in more detail below.

140. Baker is directed to a “catalyst composition comprising support particles having at least one catalytically active metal distributed therein” wherein the “catalyst composition [is] suitable for the manufacture of vinyl acetate may also comprise . . . promoters.” Baker, 1:60-67, 4:66-5:12. Baker further teaches that the active metal is a Group VIII noble metal, which “is distributed in the support particle . . . between an inner and an outer region of said support particle” such that the inner region has a lower concentration of the Group VIII noble metal.

Id. Figure 1 depicts this structure where the layer of Group VIII noble metal (2) is “located with an outer edge (7) below the particle surface (3) and between an inner region (4) and an outer region (5) of the catalyst particle having lower concentrations of the Group VIII noble metal and/or other metals than the layer (2).” *Id.*, FIG 1, 7:35-53. Thus, Baker teaches a



non-uniform particle wherein the concentration of noble metal is lowest at the center “inner region” of the particle and the concentration of noble metal increases radially to the outer edge (7) relative to the inner region (4). *Id.* Indeed, the ’864 Patent recognizes that the gradation of the noble metal from the higher concentration in the outer region to the lower concentration in the core is not a

binary requirement but a relative measurement such that the active metal is *not* uniformly distributed in the particle. '864 patent, 3:14-22.

2. Combination of Miura and Baker

141. As described above, Miura discloses “an exhaust gas purifying catalyst and a process for producing a metal oxide particle comprising multiple species of metal oxides and capable of satisfactorily exerting the properties of respective metal oxides.” Miura, Abstract. Miura teaches that the disclosed exhaust purifying catalyst is capable of oxidizing CO. *Id.*, [0002]. Miura further teaches an “eggshell” structure of the catalyst wherein the surface layer of particulate support comprises CeO₂, which covers an entire core part formed of ZrO₂, and a noble metal, such as platinum, is supported on the particulate support. *Id.*, FIG 2, [0068].

142. Miura additionally discloses a range of average particle diameters of the metal oxide particles as, “less than 10 μm, less than 5 μm, less than 1 μm, less than 500 nm, less than 200 nm, less than 100 nm or less than 50 nm,” and teaches the benefits of small particle size. *Id.*, [0015], [0068]. Therefore, Miura discloses particles having an average diameter size of less than 1mm. However, Miura does not expressly teach the full range of the claimed particle size. Yet, a POSITA still would have appreciated that Miura teaches benefits of using small particle size in

the disclosed combustion promoter. Miura, [0068]. Therefore, a POSITA would have considered using the disclosed particle sizes taught by Baker.

143. Like Miura, Baker discloses a “catalyst composition comprising support particles having at least one catalytically active metal distributed therein,” wherein the “catalyst composition suitable for the manufacture of vinyl acetate may also comprise . . . promoters.” Baker, 1:60-67, 4:66-5:12. Baker discloses a non-uniformly distributed metal catalyst structure, which, similar to Miura, discloses a lower concentration of metal in the center of the particle. Baker teaches that the Group VIII noble metal “is distributed in the support particle . . . between an inner and an outer region of said support particle” such that the inner region has a lower concentration of the Group VIII noble metal than the outer region. *Id.*, 1:60-67, 4:39-47.

144. As to the average particle size, Baker further teaches that the support particles are “microspheroidal.” *Id.*, 3:34-46. Baker specifically teaches that the catalyst has the following particle size distribution:

0 to 20 microns	0-30 wt %
20 to 44 microns	0-60 wt %
44 to 88 microns	10-80 wt %
88 to 106 microns	0-80 wt %
>106 microns	0-40 wt %
>300 microns	0-5 wt %

id., 3:16-33, wherein the average particle size is approximately 73 microns.

Therefore, Baker teaches microsphere sized porous particles having an average

diameter size of less than 1mm. A POSITA would have recognized the particles with an average size less than 1mm may be used in conjunction with the eggshell catalyst of Miura. *Id.* Moreover, Miura and Baker both teach similar components of the combustion promoters, including silica, aluminum, and Group VIII metals, as described below, and Miura teaches benefits of small particle diameter. Miura, [0068]. By incorporating the specific particle size ranges of Baker into Miura, a POSITA would have recognized that the properties of Miura's eggshell catalyst can be improved through the specific particle size teachings of Baker.

145. A POSITA would have been further prompted to pursue this implementation of Baker's specific particle size into Miura's combustion promoter because doing so is merely the application of known techniques (*e.g.*, using small particles) to a known structure (*e.g.*, combustion promoter material) to yield predictable results (*e.g.*, improved performance). And a POSITA would have had a reasonable expectation of success in the Miura-Baker combination given that both Miura and Baker already describe using sub-1mm particles for improved catalytic performance.

3. Analysis

(i) Claim 1

[1pre] A CO to CO₂ combustion promoter comprising microsphere sized porous particles, each microsphere sized porous particle having a diameter of less than 1mm, and independently comprising:

146. To the extent the preamble is deemed limiting, Miura-Baker renders obvious a CO to CO₂ combustion promoter comprising microsphere sized porous particles, each microsphere sized porous particle having a diameter of less than 1mm. For example, Miura discloses “an exhaust gas purifying catalyst and a process for producing a metal oxide particle comprising multiple species of metal oxides and capable of satisfactorily exerting the properties of respective metal oxides.” Miura, Abstract. Miura further discloses that the disclosed exhaust purifying catalyst is capable of oxidizing CO. *Id.*, [0002]. Miura additionally discloses a range of average particle diameters of the metal oxide particles as, “less than 10 μm, less than 5 μm, less than 1 μm, less than 500 nm, less than 200 nm, less than 100 nm or less than 50 nm,” and teaches the benefits of small particle size. *Id.*, [0015], [0068]; therefore, Miura discloses particles having an average diameter size of less than 1mm. However, Miura does not expressly teach the full range of the claimed particle size.

147. Baker discloses a “catalyst composition comprising support particles having at least one catalytically active metal distributed therein,” wherein the “catalyst composition suitable for the manufacture of vinyl acetate may also comprise . . . promoters.” Baker, 1:60-67, 4:66-5:12. Baker further teaches that the support particles are “microspheroidal.” *Id.*, 3:34-46. Baker specifically teaches that the catalyst has the following particle size distribution:

0 to 20 microns	0-30 wt %
20 to 44 microns	0-60 wt %
44 to 88 microns	10-80 wt %
88 to 106 microns	0-80 wt %
>106 microns	0-40 wt %
>300 microns	0-5 wt %

id., 3:16-33, wherein the average particle size is approximately 73 microns.

Therefore, Baker teaches microsphere sized porous particles having an average diameter size of less than 1mm.

[1a] silica, alumina, or mixtures thereof; and

148. In the Miura-Baker combination, as described above, Miura discloses silica, alumina, or mixtures thereof.

149. Further, Baker discloses silica, alumina, or mixtures thereof. Baker discloses a catalyst composition comprising support particles having at least one catalytically active metal distribution therein where “*silica-based support particles* are the most preferred.” Baker, 1:60-67, 4:8-36. Baker further teaches that the support particles include “*alumina, silica-alumina*, ceria, magnesia, titania, zirconia and mixed oxides and mixtures thereof.” *Id.*; *see also id.*, 1:12-22.

[1b] one or more Group VIII noble metals distributed in the particle as an eggshell such that a higher concentration of the one or more Group VIII noble metals is present in the outer region of the microsphere sized porous particle as compared to the concentration of the one or more Group VIII noble metals in the centre of the microsphere sized porous particle.

150. As described above, in the Miura-Baker combination, Miura discloses one or more Group VIII noble metals distributed in the particle as an eggshell such

that a higher concentration of the one or more Group VIII noble metals is present in the outer region of the microsphere sized porous particle as compared to the concentration of the one or more Group VIII noble metals in the centre of the microsphere sized porous particle.

(ii) Claim 2

[2] The combustion promoter according to claim 1, comprising a plurality of microsphere sized porous particles comprising silica.

151. In the Miura-Baker combination, Baker discloses the combustion promoter includes a plurality of microsphere sized porous particles comprising silica. Baker discloses a catalyst composition comprising support particles having at least one catalytically active metal distribution therein where “*silica-based support particles* are the most preferred.” Baker, 1:60-67, 4:8-36.

(iii) Claim 3

[3] The combustion promoter according to claim 1, comprising a plurality of microsphere sized porous particles comprising alumina.

152. In the Miura-Baker combination, and as I described above, Miura discloses the combustion promoter comprising a plurality of microsphere sized porous particles comprising alumina.

153. Further, Baker discloses the combustion promoter comprising a plurality of microsphere sized porous particles comprising alumina. Baker discloses a catalyst composition comprising support particles having at least one catalytically active metal distribution therein where the support particles include

“*alumina, silica-alumina*, ceria, magnesia, titania, zirconia and mixed oxides and mixtures thereof.” Baker, 1:60-67, 4:8-36; *see also id.*, 1:12-22.

(iv) Claim 4

[4] The combustion promoter according to claim 1, comprising a first plurality of microsphere sized porous particles comprising silica and a second plurality of microsphere sized porous particles comprising alumina.

154. In the Miura-Baker combination, Baker discloses a combustion promoter including a first plurality of microsphere sized porous particles comprising silica and a second plurality of microsphere sized porous particles comprising alumina. For example, Baker discloses a catalyst composition comprising support particles having at least one catalytically active metal distribution therein where “*silica-based support particles* are the most preferred.” Baker, 1:60-67, 4:8-36. Baker further teaches that the support particles include “*alumina, silica-alumina*, ceria, magnesia, titania, zirconia and mixed oxides and *mixtures thereof*.” *Id.*; *see also id.*, 1:12-22.

(v) Claim 5

[5] The combustion promoter according to claim 1, comprising a plurality of microsphere sized porous particles comprising silica and alumina.

155. In the Miura-Baker combination, Baker discloses the combustion promoter including a plurality of microsphere sized porous particles comprising silica and alumina. For example, Baker discloses a catalyst composition comprising support particles having at least one catalytically active metal

distribution therein where “*silica-based support particles* are the most preferred.”

Baker, 1:60-67, 4:8-36. Baker further teaches that the support particles include

“alumina, *silica-alumina*, ceria, magnesia, titania, zirconia and mixed oxides and *mixtures thereof*.” *Id.*; see also *id.*, 1:12-22.

(vi) Claim 6

[6] The combustion promoter according to claim 1, wherein the microsphere sized porous particles collectively have an average (D50) size of between 60 and 90 microns as measured by laser diffraction.

156. In the Miura-Baker combination, Baker discloses “catalyst composition comprising support particles having at least one catalytically active metal distributed therein” wherein the layer of Group VIII noble metal (2) is “located with an outer edge (7) below the particle surface (3) and between an inner region (4) and an outer region (5).” Baker, 1:60-67, 3:34-46, 7:35-53. Baker specifically teaches that its catalyst has the following particle size distribution:

0 to 20 microns	0-30 wt %
20 to 44 microns	0-60 wt %
44 to 88 microns	10-80 wt %
88 to 106 microns	0-80 wt %
>106 microns	0-40 wt %
>300 microns	0-5 wt %

as measured by laser diffraction, wherein the average particle size is approximately 73 microns. Baker, 3:16-33 (“Particle sizes and particle size distributions may be measured by an automated laser device such as a Microtrac X100.”). Baker therefore teaches an average (D50) size of between 60 and 90 microns.

(vii) Claim 7

[7] The combustion promoter according to claim 1, wherein the microsphere sized porous particles are gamma or theta alumina particles.

157. As described above, in the Miura-Baker combination, Miura discloses the combustion promoter wherein the microsphere sized porous particles are gamma or theta alumina particles.

(viii) Claim 8

[8] The combustion promoter according to claim 1, wherein the microsphere sized porous particles are spray dried silica particles.

158. In the Miura-Baker combination, Baker discloses the combustion promoter wherein the microsphere sized porous particles are spray dried silica particles. For example, Baker discloses that a “suitable support material for use in a fluid bed process is a microspheroidal particulate material” wherein the “microspheroidal particles are produced by *spray drying a mixture of a silica sol with silica particles* followed by drying and calcining.” Baker, 2:63-3:10, 3:40-45. Baker further teaches an example of preparing the microspheroidal support particles “by *spray-drying a mixture of Nalco silica sol 1060 . . . and Degussa Aerosil® silica.*” *Id.*, 7:56-67.

(ix) Claim 12

[12] The combustion promoter according to claim 1, wherein the one or more Group VIII noble metals comprises one or more of platinum, palladium, iridium, ruthenium, and rhodium.

159. In the Miura-Baker combination, and as I described above, Miura discloses the combustion promoter wherein the one or more Group VIII noble metals comprises one or more of platinum, palladium, iridium, ruthenium, and rhodium.

160. Further, Baker also discloses the combustion promoter wherein the one or more Group VIII noble metals comprises one or more of platinum, palladium, iridium, ruthenium, and rhodium. For example, Baker discloses “catalyst composition comprising support particles having at least one catalytically active metal distributed therein” such that the metal is preferably a Group VIII noble metal. Baker, 1:60-67, 4:39-47. Baker teaches that Group VIII noble metals comprising the catalytically active metal are “*palladium, platinum, rhodium, ruthenium*, osmium and iridium.” *Id.* Baker further teaches that supported metal catalysts, including the disclosed composition, are typically “made by impregnating a support such as silica or alumina with a compound of a Group VIII noble metal such as *palladium* together with a gold compound and an alkali metal salt.” *Id.*, 1:12-22.

(x) Claim 13

[13] The combustion promoter according to claim 12, wherein the one or more Group VIII noble metals comprises platinum and palladium.

161. As described above, in the Miura-Baker combination, Miura discloses the combustion promoter wherein the one or more Group VIII noble metals comprises platinum and palladium.

162. Further, Baker discloses the combustion promoter wherein the one or more Group VIII noble metals comprises platinum and palladium. For example, Baker discloses “catalyst composition comprising support particles having at least one catalytically active metal distributed therein” such that the metal is preferably a Group VIII noble metal. Baker, 1:60-67, 4:39-47. Baker teaches that Group VIII noble metals comprising the catalytically active metal are “*palladium, platinum, rhodium, ruthenium, osmium and iridium.*” *Id.*

(xi) Claim 14

[14] The combustion promoter according to claim 12, wherein the one or more Group VIII noble metals comprises platinum.

163. In the Miura-Baker combination, and as I described above, Miura discloses the combustion promoter wherein the one or more Group VIII noble metals comprises platinum.

164. Further, Baker discloses claim 14. For example, Baker discloses “catalyst composition comprising support particles having at least one catalytically active metal distributed therein” such that the metal is preferably a Group VIII noble metal. Baker, 1:60-67, 4:39-47. Baker teaches that Group VIII noble metals

comprising the catalytically active metal are “palladium, *platinum*, rhodium, ruthenium, osmium and iridium.” *Id.*

(xii) Claim 15

[15] The combustion promoter according to claim 12, wherein the one or more Group VIII noble metals comprises palladium.

165. In the Miura-Baker combination, and as I described above, Miura discloses the combustion promoter wherein the one or more Group VIII noble metals comprises palladium.

166. Further, Baker discloses claim 15. For example, Baker discloses “catalyst composition comprising support particles having at least one catalytically active metal distributed therein” such that the metal is preferably a Group VIII noble metal. Baker, 1:60-67, 4:39-47. Baker teaches that Group VIII noble metals comprising the catalytically active metal are “*palladium*, platinum, rhodium, ruthenium, osmium and iridium.” *Id.* Baker further teaches that supported metal catalysts, including the disclosed composition, are typically “made by impregnating a support such as silica or alumina with a compound of a Group VIII noble metal such as *palladium* together with a gold compound and an alkali metal salt.” *Id.*, 1:12-22.

(xiii) Claim 16

[16] The combustion promoter according to claim 1, wherein the microsphere sized porous particles further comprise at least one of cerium oxide and copper oxide.

167. In the Miura-Baker combination, and as I described above, Miura discloses the combustion promoter wherein the microsphere sized porous particles further comprise at least one of cerium oxide and copper oxide.

168. Further, Baker discloses claim 16. Baker discloses “catalyst composition comprising support particles having at least one catalytically active metal distributed therein” such that the metal is preferably a Group VIII noble metal. Baker, 1:60-67, 4:39-47. Baker further teaches that the Group VIII noble metal “is distributed in the support particle . . . between an inner and an outer region of said support particle” such that the inner region has a lower concentration of the Group VIII noble metal. *Id.* Baker further teaches that the support particles include “alumina, silica-alumina, *ceria*, magnesia, titania, zirconia and *mixed oxides* and mixtures thereof,” and other oxides may be used including “other metals such as gold, *copper*, *cerium* and mixtures thereof.” *Id.*, 4:8-36, 4:66-5:12. A POSITA would understand the scope of Baker to include support particles comprising cerium oxide and copper oxide.

(xiv) Claim 17

[17] The combustion promoter according to claim 16, wherein the at least one of cerium oxide and copper oxide is distributed in the microsphere sized porous particle as an eggshell such that a higher concentration of the at least one of cerium oxide and copper oxide is present in the outer region of the microsphere sized porous particle as compared to the concentration of the at least one of cerium oxide and copper oxide in the centre of the microsphere sized porous particle.

169. As described above, in the Miura-Baker combination, Miura discloses the combustion promoter wherein the at least one of cerium oxide and copper oxide is distributed in the microsphere sized porous particle as an eggshell such that a higher concentration of the at least one of cerium oxide and copper oxide is present in the outer region of the microsphere sized porous particle as compared to the concentration of the at least one of cerium oxide and copper oxide in the center of the microsphere sized porous particle.

(xv) Claim 18²

[18pre] The combustion promoter according to claim 1, obtained by a process comprising the following steps:

170. As I described above, in the Miura-Baker combination, Miura discloses the preamble of claim 18.

[18a] introducing a medium in the pores of microsphere sized porous particles having a diameter of less than 1 mm to obtain microsphere sized porous particles with filled pores; and

171. As discussed above, Miura-Baker renders obvious introducing a medium in the pores of microsphere sized porous particles having a diameter of less than 1 mm to obtain microsphere sized porous particles with filled pores. For example, Miura discloses “an exhaust gas purifying catalyst and a process for

² Miura-Baker renders obvious claim 18 because the combination renders obvious claim 1. *See* MPEP § 2113.

producing a metal oxide particle comprising multiple species of metal oxides and capable of satisfactorily exerting the properties of respective metal oxides.” Miura, Abstract. Miura additionally discloses a range of average particle diameters of the metal oxide particles as, “less than 10 μm , less than 5 μm , less than 1 μm , less than 500 nm, less than 200 nm, less than 100 nm or less than 50 nm,” and teaches the benefits of small particle size. *Id.*, [0015], [0068]. Therefore, Miura discloses particles having an average diameter size of less than 1mm. Miura further discloses a surface layer of particulate support and a noble metal supported on the particulate support, wherein the “noble metal can be supported by dispersing the particulate support in distilled water and adding a noble metal solution.” Miura, FIG 2, [0068], [0072].

172. Further, Baker teaches that the support particles are “microspheroidal.” *Id.*, 1:60-67, 3:34-46. Baker specifically teaches that the catalyst has the following particle size distribution:

0 to 20 microns	0-30 wt %
20 to 44 microns	0-60 wt %
44 to 88 microns	10-80 wt %
88 to 106 microns	0-80 wt %
>106 microns	0-40 wt %
>300 microns	0-5 wt %

id., 3:16-33, wherein the average particle size is approximately 73 microns.

Therefore, Baker teaches microsphere sized porous particles having an average diameter size of less than 1mm. Baker discloses that the “catalytically active

metal(s) may be impregnated in one or more steps onto the support particles in the form of precursor salt solutions” wherein the preferably medium is a palladium compound in a suitable solvent, such as water, carboxylic acids, alcohols, nitriles, or chlorinated solvents. Baker, 4:48-65.

[18b] contacting the microsphere sized porous particles with filled pores with an aqueous salt solution of the one or more Group VIII noble metals,

173. As I described above, in the Miura-Baker combination, Miura discloses contacting the microsphere sized porous particles with filled pores with an aqueous salt solution of the one or more Group VIII noble metals.

174. Further, Baker discloses contacting the microsphere sized porous particles with filled pores with an aqueous salt solution of the one or more Group VIII noble metals. For example, Baker discloses that the “catalytically active metal(s) may be impregnated in one or more steps onto the support particles in the form of precursor *salt solutions*” wherein the preferably medium is a *palladium compound in a suitable solvent*, such as water, carboxylic acids, alcohols, nitriles, or chlorinated solvents. Baker, 4:48-65. Baker further discloses that the pores may be filled repeatedly with salt solution in order to achieve the desired level of metal in the impregnated particles. *Id.* at 5:42-65.

[18c] wherein the one or more Group VIII noble metals deposits at a higher content in the outer region of the microsphere sized porous particles with filled pores as compared to the content of the one or more Group VIII noble metals in the centre of the microsphere sized porous particles with filled pores, thereby obtaining eggshell particles.

175. As I described above, in the Miura-Baker combination, Miura discloses wherein the one or more Group VIII noble metals deposits at a higher content in the outer region of the microsphere sized porous particles with filled pores as compared to the content of the one or more Group VIII noble metals in the center of the microsphere sized porous particles with filled pores, thereby obtaining eggshell particles.

(xvi) Claim 19

[19] The combustion promoter of claim 18, the process further comprising a step: (c) at least one of drying and calcining the eggshell particles.

176. As I described above, in the Miura-Baker combination, Miura discloses the process further comprising a step: (c) at least one of drying and calcining the eggshell particles.

177. Further, Baker discloses the process further comprising a step: (c) at least one of drying and calcining the eggshell particles. Baker discloses that the *“impregnated support particles may optionally be dried”* wherein the “drying step may be performed at up to 140° C., preferably up to 120° C” and “may be performed at ambient temperature and reduced pressure.” Baker, 5:55-65.

(xvii) Claim 20

[20] The combustion promoter according to claim 18, wherein the microsphere sized porous particles having pores filled in step (a) are gamma alumina particles having an average (D50) size of between 60 and 90 microns, have a surface area (BET) of between 50 and 300 m²/g, and a pore volume of between 0.05 and 0.50 mL/g as measured by the water pore volume.

178. Miura-Baker renders obvious claim 20. First, Miura-Baker teaches the claimed particles. For example, Miura discloses, as known in the art, “three-way catalysts where a noble metal such as platinum (Pt), rhodium (Rh) and palladium (Pd) is supported *on a porous metal oxide support such as γ -alumina.*” Miura, [0002]. Baker discloses a “catalyst composition comprising support particles having at least one catalytically active metal distributed therein” wherein the layer of Group VIII noble metal (2) is “located with an outer edge (7) below the particle surface (3) and between an inner region (4) and an outer region (5).” Baker, 1:60-67, 3:34-46, 7:35-53. Baker further teaches that the “layer has an average thickness which is less than half the radius of the particle, for example less than 25 microns.” *Id.*, 2:41-58. Therefore, a POSITA would understand that if half of the radius of the particle is less than 25 microns, the diameter is less than 100 microns. Moreover, Baker specifically teaches that the catalyst has the following particle size distribution:

0 to 20 microns	0-30 wt %
20 to 44 microns	0-60 wt %
44 to 88 microns	10-80 wt %
88 to 106 microns	0-80 wt %
>106 microns	0-40 wt %
>300 microns	0-5 wt %

Baker, 3:16-33, wherein the average particle size is approximately 73 microns. Baker therefore teaches an average (D50) size of between 60 and 90 microns. A POSITA would have recognized that the γ -alumina particles with an average

particle size between 60 and 90 microns may be used. Namely, Miura teaches the use of γ -alumina particles and also teaches the benefits of small particle diameter. Miura, [0068]. Thus, a POSITA would have been motivated to combine the small γ -alumina particles, as described by Miura, with the average particle size distribution disclosed by Baker.

179. Second, Baker discloses the claimed surface area. Baker discloses the surface area of support particles is typically “about 50 m²/g and may range up to about 200 m²/g . . . and may range up to about 800 m²/g.” Baker, 3:41-51, 4:18-28. Therefore, a POSITA would have recognized that Baker teaches a complete overlap with the claimed surface area.

180. Third, Baker discloses the claimed pore volume. Baker discloses that a “typically suitable microspheroidal support particle has a pore volume (measured by nitrogen sorption) between about 0.2 and 0.7 cc/g.” *Id.*, 3:41-51, 4:18-28. A POSITA would understand that the volume measurement cc/g is equivalent to mL/g. Therefore, a POSITA would have recognized that Baker teaches an overlap of the claimed pore volume.

(xviii) Claim 21

[21] The combustion promoter according to claim 18, wherein the medium in step (a) is water.

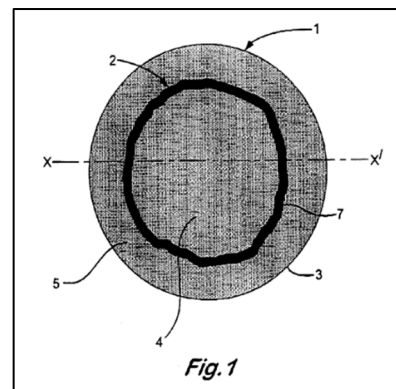
181. As I described above, in the Miura-Baker combination, Miura discloses that in the combustion promoter the medium in step (a) is water.

182. Further, Baker discloses that in the combustion promoter the medium in step (a) is water. Baker discloses that the “catalytically active metal(s) may be impregnated in one or more steps onto the support particles in the form of precursor salt solutions” wherein the preferably medium is a palladium compound in a suitable solvent, such as water, carboxylic acids, alcohols, nitriles, or chlorinated solvents. *Id.*, 4:48-65. Baker specifically teaches that “[p]referably, the solvent is water.” *Id.*

(xix) Claim 22

[22] The combustion promoter according to claim 18, wherein in step (b) the filled microsphere sized porous particles are contacted in step (b) with a volume of the aqueous salt solution of the one or more Group VIII noble metals which is less than the total volume of the pores of the starting microsphere sized particles.

183. Miura-Baker renders obvious the combustion promoter wherein in step (b) the filled microsphere sized porous particles are contacted in step (b) with a volume of the aqueous salt solution of the one or more Group VIII noble metals which is less than the total volume of the pores of the starting microsphere sized particles. Baker discloses that the “catalytically active metal(s) may be impregnated in one or more steps onto the support particles in the form of precursor *salt solutions*” wherein preferably the medium is a *palladium compound in a suitable solvent*, such as water, carboxylic acids, alcohols,



nitriles, or chlorinated solvents. *Id.*, 4:48-65. Baker further teaches that a “preferable method to impregnate salt solutions is an incipient wetness technique in which there is used a salt solution in an amount ***up to the volume of the pores*** of the support particles ***without excess solution being used.***” *Id.*, 5:42-54. Baker explains the goal of this method to obtain a “desirable level of metal compounds, such as palladium” incorporated into the support particles on the outer edge (7) below the particle surface (3), as depicted in Figure 1. *Id.*, 5:42-54, 7:35-53. A POSITA would have understood that in order to incorporate a desirable level of metal compound into the support particle on the outer edge, the salt solution must be up to or less than the total volume of the pores of the starting microsphere sized particles. For example, a POSITA would have understood the deviating from the teaching of Baker and using excess solution more than the total volume of the pores would prevent the deposition of the metal compound on the outer edge of the support particle. Moreover, a POSITA would have recognized that Baker teaches a range of volume of salt solution that is less than or equal to the pore volume of the particles.

**L. [GROUND 2A] – CLAIM 9 IS OBVIOUS OVER MIURA
IN VIEW OF BAKER AND IN FURTHER VIEW OF
VAUGHN 290**

184. It is my opinion that a POSITA would have found claim 9 to be obvious over Miura and Baker and in further view of Vaughn 290, as I discuss in the following sections.

1. Combination of Miura, Baker, and Vaughn 290

185. It is my opinion that a POSITA would have been motivated to use the equilibrium or spent catalyst particles, such as those described by Vaughn 290, to the eggshell catalyst particles disclosed in Miura-Baker for at least the reasons I discuss below.

186. As described above, a POSITA would have been motivated to combine the recycling process of Vaughn 290 to the eggshell catalyst of Miura. Likewise, a POSITA would have been motivated to combine the recycling process of Vaughn 290 to the combination of Miura-Baker. Baker discloses a non-uniform structure similar to that of Miura, wherein the “catalyst composition comprising support particles hav[e] at least one catalytically active metal distributed therein” wherein the “catalyst composition [is] suitable for the manufacture of vinyl acetate may also comprise . . . promoters.” Baker, 1:60-67, 4:66-5:12. Vaughn 290, similar to Miura and Baker, discloses a catalyst which contains molecular sieve-containing attrition particles and virgin molecular sieve, the attrition particles

having been recycled from a catalyst manufacture process or from a reaction system.” Vaughn 290, 1:7-13. Vaughn 290 further teaches that the disclosed catalyst may be used in a variety of catalytic reaction processes such that the recycled catalyst particles can be used to form a catalytic composition. *Id.*, Abstract, 2:43-45. A POSITA would have recognized the variety of catalytic reaction processes as including a CO to CO₂ combustion promoter. In addition, Vaughn 290 discloses *recycled* particles that “are actually molecular sieve-containing catalyst particles that have been [sic] used in a functioning manufacture or reaction system, and have been reduced in size due to attrition.” Vaughn 290, 9:55-65. Vaughn 290 discloses that the “catalyst fines are recovered from the manufacture or reaction system and are recycled back into the catalyst manufacturing scheme. The catalyst fines, therefore, are incorporated into the finished catalyst particles.” Vaughn 290, 9:55-65, 16:26-35. While Miura-Baker does not disclose an equilibrium or spent catalyst, a POSITA would have understood that “the recovery and use of the attrition particles in [a] catalyst is beneficial in minimizing waste, thereby reducing problems relating to both environmental and economic constraints.” Vaughn 290, Abstract.

187. By incorporating the recycling teachings of Vaughn 290 into Miura-Baker, a POSITA would have recognized the efficiencies and benefits of recycling catalyst material in combination with Miura’s and/or Baker’s non-uniform catalyst.

Indeed, Vaughn 290 teaches that “the recovery and use of the attrition particles in [a] catalyst is beneficial in minimizing waste, thereby reducing problems relating to both environmental and economic constraints.” Vaughn 290, Abstract. Miura discloses that a “noble metal [13, shown in Fig. 2] such as platinum, rhodium and palladium is supported on the metal oxide particle. . . [and] mainly on the surface layer [12].” Miura, [0048], [0072], Fig. 2. Baker likewise teaches depositing noble metals, such as “palladium, platinum, rhodium, ruthenium, osmium and iridium,” in a *non-uniform* particle wherein the concentration of noble metal is lowest at the center “inner region” of the particle. Baker, FIG 1, 1:60-67, 4:39-47, 7:35-53.

188. A POSITA would have recognized the expense of the noble metals disclosed in Miura and Baker and appreciate the cost-saving efficiencies that both teach by depositing the noble metal on the surface or outer edge of the particle, rather than uniformly distributed throughout the particles. This cost-saving measure of Miura and Baker would have motivated a POSITA to apply additional efficiencies to the preparation of the catalyst particles, namely the recycling process disclosed by Vaughn 290.

189. A POSITA would have been further prompted to pursue the efficiencies of Vaughn 290 as doing so is merely the application of known techniques (*e.g.*, recycling combustion promoter particles) to a known structure

(e.g., the combustion promoter particles) to yield predictable results (e.g., minimizing waste). And a POSITA would have had a reasonable expectation of success in the Miura-Baker-Vaughn 290 combination given that each reference describes catalyst for use in a variety of catalytic reaction processes, including well-known CO to CO₂ combustion promotion process. *See* Miura, Abstract, [0014]; Baker, 1:60-67, 4:66-5:12; Vaughn 290, Abstract, 2:43-45.

2. Analysis

(i) Claim 9

[9] The combustion promoter according to claim 1, wherein the microsphere sized porous particles are an equilibrium or spent catalyst as obtained from a fluidized catalytic cracking (FCC) process.

190. Miura-Baker-Vaughn 290 renders obvious the combustion promoter wherein the microsphere sized porous particles are an equilibrium or spent catalyst as obtained from a fluidized catalytic cracking (FCC) process. As discussed above, Miura-Baker renders obvious the combustion promoter according to claim 1. Further, as discussed above, Vaughn 290 renders obvious an equilibrium or spent catalyst as obtained from a fluidized catalytic cracking (FCC) process.

M. [GROUND 2B] – CLAIMS 10 & 11 ARE OBVIOUS OVER MIURA IN VIEW OF BAKER AND IN FURTHER VIEW OF PETERS OR, ALTERNATIVELY, VAUGHN 516

191. It is my opinion that a POSITA would have found claims 10 and 11 to be obvious over Miura and Baker and in further view of Peters or, alternatively, Vaughn 516, as I discuss in the following sections.

1. Combination of Miura, Baker, and Peters

192. It is my opinion that a POSITA would have recognized the attrition value of catalyst particles, such as those described by Peters, to the eggshell catalyst particles disclosed in Miura-Baker and would have been motivated to combine the two references for at least the reasons I discuss below.

193. As described above, a POSITA would have been motivated to combine the attrition index value explicitly disclosed in Peters to the combustion promoter of Miura. Likewise, a POSITA would have been motivated to combine the attrition index value of Peters to the combination of Miura-Baker. Baker discloses a non-uniform structure similar to that of Miura, wherein the “catalyst composition comprising support particles hav[e] at least one catalytically active metal distributed therein” wherein the “catalyst composition [is] suitable for the manufacture of vinyl acetate may also comprise . . . promoters.” Baker, 1:60-67, 4:66-5:12. Similar to Miura and Baker, Peters discloses “compositions suitable for use in FCC processes which are capable of promoting CO combustion while avoiding significant NO_x formation.” Peters, 1:49-60. Further, Peters teaches the use of similar components of the combustion promoter, namely, the use of ceria as the preferred oxide component as the outer layer (most susceptible to attrition) of the eggshell structure disclosed by Miura-Baker. *See* Miura, [0068]; Baker, 4:8-36, 4:66-5:12; Peters, 1:49-60. And while Miura-Baker is silent as to the attrition

index, Peters explicitly identifies the attrition index value of the combustion promoter composition. Peters, 3:9-20. A POSITA would have understood that catalyst material should be durable and attrition-resistant and therefore a low attrition index is desirable, while reducing NO_x emissions.

194. A POSITA would have understood that Miura teaches the use of ceria as the outer portion of the particle and, thus, the surface layer most susceptible to attrition. For example, Miura discloses that the surface layer 12 (i.e., outer region) is relatively rich in particles “selected from the group consisting of alumina, ceria, zirconia and titania colloid particles,” and may particularly be ceria (i.e., cerium oxide). Miura, [0023]-[0026], Fig. 2. Miura depicts its resulting structure—referred to in the art as an “eggshell”—in Fig. 2, depicting a surface layer (12) of particulate support comprising CeO₂ which covers an entire core part (11) formed of ZrO₂ or alternatively, alumina, and a noble metal (13), such as platinum, supported on the particulate support. *Id.*, FIG 2, [0068], [0023]-[0026]. In this manner, as shown and described with respect to Fig. 2, Miura teaches or suggests that the cerium oxide is distributed in the particle as an eggshell such that a higher concentration of the cerium oxide is present in the surface layer 12 (i.e., the outer region) as compared to the concentration of the cerium oxide in the center of the particle. *Id.*, FIG 2, [0068], [0023]-[0026]. A POSITA would thereby have understood the disclosure of Miura would have similar attrition properties to the

value disclosed by Peters where Peters likewise teaches the use of ceria as a component of the catalyst particle.

195. By incorporating the specific attrition index teachings of Peters to Miura-Baker, a POSITA would have recognized that the attrition index value of Miura-Baker, using the same cerium oxide as the outer layer of the combustion particles, would have been similar or equivalent to the values disclosed in Peters. A POSITA would have been further prompted to pursue the optimal attrition index of the combustion promoter particles as doing so is merely the application of known techniques (*e.g.*, standard attrition measurement) to a known structure (*e.g.*, the combustion promoter particles) to yield predictable results (*e.g.*, improved attrition properties). '864 patent, 6:53-63. And a POSITA would have expected success in the Miura-Baker-Peters combination given that both already describe using cerium oxide as the preferred metal oxide component of the combustion promoter. *See* Miura, [0068]; Peters, 1:49-60.

2. Combination of Miura, Baker, and Vaughn 516

196. It is my opinion that a POSITA would have recognized the attrition value of catalyst particles, such as those described by Vaughn 516, to the eggshell catalyst particles disclosed in Miura-Baker and would have been motivated to combine the two references for at least the reasons I discuss below.

197. As described above, a POSITA would have been motivated to combine the attrition index value explicitly disclosed in Vaughn 516 to the combustion promoter of Miura. Likewise, a POSITA would have been motivated to combine the attrition index value of Vaughn 516 to the combination of Miura-Baker. Baker discloses a non-uniform structure similar to that of Miura, wherein the “catalyst composition comprising support particles hav[e] at least one catalytically active metal distributed therein” wherein the “catalyst composition [is] suitable for the manufacture of vinyl acetate may also comprise . . . promoters.” Baker, 1:60-67, 4:66-5:12. Similar to Miura, a POSITA would have recognized that Baker teaches that the core part of the particle is does not contain or has a low concentration of the noble metal component, specifically platinum and palladium, that are present on the surface of the particle. *Id.*, 2:41-58, Fig. 2. Vaughn 516 is directed to processes for removing undesirably sized catalyst particles from a catalyst synthesis system; in particular, Vaughn 516 discloses a molecular sieve to obtain a slurry of optimally-sized catalyst particles. Vaughn 516, Abstract. In particular, Vaughn 516 teaches an embodiment wherein the particle size of the molecular sieve catalyst particles, which overlaps with the particle size disclosed by Miura, and, separately, teaches a particle size that overlaps with Baker. Vaughn 516, [0011], [0014], [0075]; Miura, [0015], [0068]; Baker, 3:16-33. Vaughn 516 teaches that the benefit of the disclosed processes is to

obtain a formulated catalyst mixture with desirable catalytic activity characteristics for use in a reaction system. *Id.*

198. Similar to Miura and Baker, Vaughn 516 teaches the use of similar components of the catalyst particles, namely, the matrix or support material contains alumina or silica. *See* Miura, [0003], [0014], [0023]-[0026]; Baker, 1:60-67, 4:8-36; Vaughn 516, [0085]. Likewise, Vaughn 516, similar to Miura and Baker, teaches the use of Group VIII metals, including platinum and palladium, as reactive components of the catalytic particle. Vaughn 516, [0108], [0164]; Miura, [[0048], [0072], Fig. 2]; Baker, 1:60-67, 4:39-47. And while Miura-Baker is silent as to the attrition index, Vaughn 516 explicitly identifies the attrition index value of the combustion promoter material. Vaughn 516, [0131]. A POSITA would have understood that catalyst material should be durable and attrition-resistant and therefore a low attrition index is desirable, while reducing NO_x emissions.

199. A POSITA would have understood that Miura teaches an “eggshell” structure in Fig. 2, depicting a surface layer (12) of particulate support comprising CeO₂ which covers an entire core part (11) formed of ZrO₂ or alternatively, alumina, and a noble metal (13), such as platinum, supported on the particulate support. *Id.*, FIG 2, [0068], [0023]-[0026]. In this manner, as shown and described with respect to Fig. 2, Miura teaches or suggests a low concentration of noble metal in the core of the eggshell. *Id.*, FIG 2, [0068], [0023]-[0026].

Likewise, Vaughn 516, similar to Miura, teaches the use of Group VIII metals, including platinum and palladium, such that the concentration of the Group VIII metal is low in the support material. Vaughn 516, [0108], [0164]; Miura, [[0048], [0072], Fig. 2]. Vaughn 516 specifically teaches that this design choice is effective in reducing overall catalyst cost and “increasing catalyst strength such as crush strength and attrition resistance.” Vaughn 516, [0106]. A POSITA would thereby have understood the disclosure of Miura would have similar attrition properties to the value disclosed by Vaughn 516 where Vaughn 516 likewise teaches catalytic components with similar distribution within the catalyst particle.

200. By incorporating the specific attrition index teachings of Vaughn 516 to Miura-Baker, a POSITA would have recognized that the attrition index value of Miura-Baker, using the catalytic components with similar distribution within the catalyst particle, would have been similar or equivalent to the values disclosed in Vaughn 516. A POSITA would have been further prompted to pursue the optimal attrition index of the combustion promoter particles as doing so is merely the application of known techniques (*e.g.*, standard attrition measurement) to a known structure (*e.g.*, the combustion promoter particles) to yield predictable results (*e.g.*, improved attrition properties). '864 patent, 6:53-63. And a POSITA would have expected success in the Miura-Baker-Vaughn 516 combination given that both

already describe using catalytic components with similar distribution within the combustion promoter. *See* Miura, [0068]; Vaughn 516, [0086].

3. Analysis

(i) Claim 10

[10] The combustion promoter according to claim 1, wherein the attrition index as measured according to ASTM D-5757 of the CO to CO₂ combustion promoter for a sieve fraction of combustion promoter particles of between 40 and 105 microns is between 5 and 25.

201. Miura-Baker-Peters or, alternatively, Miura-Baker-Vaughn 516 renders obvious the combustion promoter wherein the attrition index as measured according to ASTM D-5757 of the CO to CO₂ combustion promoter for a sieve fraction of combustion promoter particles of between 40 and 105 microns is between 5 and 25. As discussed above, Miura-Baker renders obvious claim 1. Further, as discussed above, Peters or Vaughn 516 renders obvious particle size between 40 and 105 microns with an attrition index between 5 and 25.

(ii) Claim 11

[11] The combustion promoter according to claim 10, wherein the attrition index of the CO to CO₂ combustion promoter for a sieve fraction of combustion promoter particles of between 40 and 105 microns is between 10 and 20.

202. Miura-Baker-Peters or, alternatively, Miura-Baker-Vaughn 516 renders obvious the combustion promoter wherein the attrition index of the CO to CO₂ combustion promoter for a sieve fraction of combustion promoter particles of between 40 and 105 microns is between 10 and 20. As discussed above, Miura-

Baker renders claim 1. Further, as discussed above, Peters or Vaughn 516 renders obvious particle size between 40 and 105 microns with an attrition index between 10 and 20.

**N. [GROUND 3] – CLAIMS 1-8 & 12-22 ARE OBVIOUS
OVER LIN IN VIEW OF BAKER**

203. It is my opinion that a POSITA would have found claims 1-8 and 12-22 to be obvious over Lin and Baker, as I discuss in the following sections.

1. Overview of Lin

204. Lin is directed to “an eggshell catalyst and process for preparation of the same,” including “single- or multiple-metal eggshell of the finished catalyst.” Lin, 1. Lin recognizes that “porous supports with active metals non-uniformly distributed have been widely studied and applied in petroleum refining and petroleum chemical industries currently.” *Id.* Lin further teaches that the “eggshell” structure is known in the art as “eggshell catalysts have been widely employed in the industrially selective hydrogenation” because the “yield and selectivity of the desired products of the above reactions can be increased by using eggshell catalysts.” *Id.*, 1-2. Indeed, Lin discloses an eggshell catalyst wherein the “[m]etal is distributed on the outer layer of the support (with eggshell shape), which is usually used in fast reactions and capable of improving the selectivity and yield of the desired products.” *Id.*

2. Combination of Lin and Baker

205. As I described above, Lin teaches that “eggshell catalysts have been widely employed in the industrially selective hydrogenation” and, in particular, discloses “an eggshell-shaped catalyst for use in selective reduction or oxidation,” including, for example, oxidation of CO. *Id.*, 1-2, 13. Lin further teaches an example wherein a catalyst was prepared using “spherical particles with diameter of 2mm.” *Id.*, 5. Lin does not expressly teach “microsphere” particle sizes of less than 1mm. Yet, a POSITA would have appreciated the use of 2mm particles in combination with the improved catalytic performance of the disclosed eggshell-shaped catalyst. *Id.*, 1-2, 13. A POSITA would have considered the similar eggshell structure of the catalyst disclosed by Lin and the similar structure taught by Baker and thereby have been motivated to use the disclosed particle sizes taught by Baker.

206. Like Lin, Baker discloses “catalyst composition comprising support particles having at least one catalytically active metal distributed therein” wherein the “catalyst composition [is] suitable for the manufacture of vinyl acetate may also comprise . . . promoters.” Baker, 1:60-67, 4:66-5:12. Baker discloses a similar non-uniform structure of the catalyst. Baker teaches that the Group VIII noble metal “is distributed in the support particle . . . between an inner and an outer

region of said support particle” such that the inner region has a lower concentration of the Group VIII noble metal. *Id.*, 1:60-67, 4:39-47.

207. As to the average particle size, Baker further teaches that the support particles are “microspheroidal.” *Id.*, 3:34-46. Baker specifically teaches that the catalyst has the following particle size distribution:

0 to 20 microns	0-30 wt %
20 to 44 microns	0-60 wt %
44 to 88 microns	10-80 wt %
88 to 106 microns	0-80 wt %
>106 microns	0-40 wt %
>300 microns	0-5 wt %

id., 3:16-33, wherein the average particle size is approximately 73 microns.

Therefore, Baker teaches microsphere sized porous particles having an average diameter size of less than 1mm. *Id.* A POSITA would have understood that the particles with an average particle size less than 1mm may be used in conjunction with the combustion promoter of Lin. *Id.* Moreover, Lin and Baker both teach similar components of the combustion promoters, including silica, aluminum, and Group VIII metals, as described below, and the improved selectivity and yield of the eggshell-shaped catalyst. Lin, 1-2. By incorporating the specific particle size range of Baker to Lin, a POSITA would have recognized that the properties of Lin’s eggshell catalyst can be improved through the specific particle size teachings of Baker.

208. A POSITA would have been further prompted to pursue this implementation of Baker's specific particle size into Lin's eggshell catalyst as doing so is merely the application of known techniques (*e.g.*, using small particles) to a known structure (*e.g.*, combustion promoter material) to yield predictable results (*e.g.*, improved performance). And a POSITA would have expected success in the Lin-Baker combination given that both Lin and Baker already describe using similarly sized particles for improved catalytic performance. For example, a POSITA would have recognized that the difference in size from 1mm to 2mm is not significant, in particular, because it was well known in the art to use particle sizes ranging by order of magnitude, as evidenced by the complete range of the microsphere sized particles as defined by the '864 Patent (*i.e.*, 1mm to zero). *Id.*

3. Analysis

(i) Claim 1

[1pre] A CO to CO₂ combustion promoter comprising microsphere sized porous particles, each microsphere sized porous particle having a diameter of less than 1mm, and independently comprising:

209. To the extent the preamble is deemed limiting, Lin-Baker renders obvious a CO to CO₂ combustion promoter comprising microsphere sized porous particles, each microsphere sized porous particle having a diameter of less than 1mm. Lin teaches that "eggshell catalysts have been widely employed in the industrially selective hydrogenation" and, in particular, discloses "an eggshell-

shaped catalyst for use in selective reduction or oxidation,” including, for example, oxidation of CO. Lin, 1-2, 13. Lin further teaches an example wherein a catalyst was prepared using “spherical particles with diameter of 2mm.” *Id.*, 5. Lin does not explicitly disclose particles with diameters below 1mm.

210. As discussed above, Baker discloses “catalyst composition comprising support particles having at least one catalytically active metal distributed therein” wherein the “catalyst composition [is] suitable for the manufacture of vinyl acetate may also comprise . . . promoters.” Baker, 1:60-67, 4:66-5:12. Baker further teaches support particles that are “microspheroidal,” and have an average particle size of approximately 73 microns. *Id.*, 1:60-67, 3:16-46.

211. A POSITA would have been motivated to use particles of size less than 1mm, as disclosed by Baker, in an eggshell-shaped catalyst, as described by Lin, in light of the small (2mm) particle size disclosed by Lin. For example, a POSITA would recognize that the difference in size from 1mm to 2mm is not significant, in particular, because it was well known in the art to use particle sizes ranging by order of magnitude, as evidenced by the complete range of the microsphere sized particles as defined by the '864 Patent (i.e., 1mm to zero). *Id.* Moreover, as I've discussed in numerous sections above, the applicant admitted that microsphere particles of diameter less than 1mm were well known in the art at the earliest effective filing date of the '864 patent.

[1a] silica, alumina, or mixtures thereof; and

212. In the Lin-Baker combination, Lin discloses silica, alumina, or mixtures thereof. For example, Lin teaches an “eggshell metal catalyst” wherein the active metal is attached to a support comprising “*Al₂O₃, SiO₂ . . . or the mixtures thereof.*” Lin, 3. Lin further discloses “various non-uniformly distributed Pt on spherical *alumina support.*” *Id.*, 2. In addition, Lin discloses an example wherein a “catalyst with linear decrease of Pd metal distribution from the outer layer toward the spherical core” comprises spherical γ -*Al₂O₃.* *Id.*, 10.

213. As I described above, Baker further discloses silica, alumina, or mixtures thereof.

[1b] one or more Group VIII noble metals distributed in the particle as an eggshell such that a higher concentration of the one or more Group VIII noble metals is present in the outer region of the microsphere sized porous particle as compared to the concentration of the one or more Group VIII noble metals in the centre of the microsphere sized porous particle.

214. In the Lin-Baker combination, Lin discloses one or more Group VIII noble metals distributed in the particle as an eggshell such that a higher concentration of the one or more Group VIII noble metals is present in the outer region of the microsphere sized porous particle as compared to the concentration of the one or more Group VIII noble metals in the center of the microsphere sized porous particle. For example, Lin discloses “an eggshell catalyst and process for preparation of the same,” including “single- or multiple-metal eggshell of the

finished catalyst.” Lin, 1. Lin further teaches that the “eggshell” structure is known in the art as and discloses an eggshell catalyst wherein the “[m]etal is distributed on the outer layer of the support (with eggshell shape), which is usually used in fast reactions and capable of improving the selectivity and yield of the desired products.” *Id.*, 1-2. Lin teaches that the metal catalysts with eggshell active metal profile “preferably comprises Pd, Ni, Co, Ho, Cu, Pt, Fe, Ag, Tr, Pb, Re, Ti, Sn, V, and Zn, etc.” *Id.*, Abstract, 3. Lin provides an example wherein the preparation of the catalyst “***with linear decrease of Pd metal distribution from outer layer toward spherical core.***” *Id.*, 10. Lin provides a comparison of a uniform particle in Figure 1 and an eggshell particle in Figure 2; Lin demonstrates the decrease of Pd metal distribution in Figure 2 showing the Pd distribution in an eggshell catalyst from electron probe microanalyser:

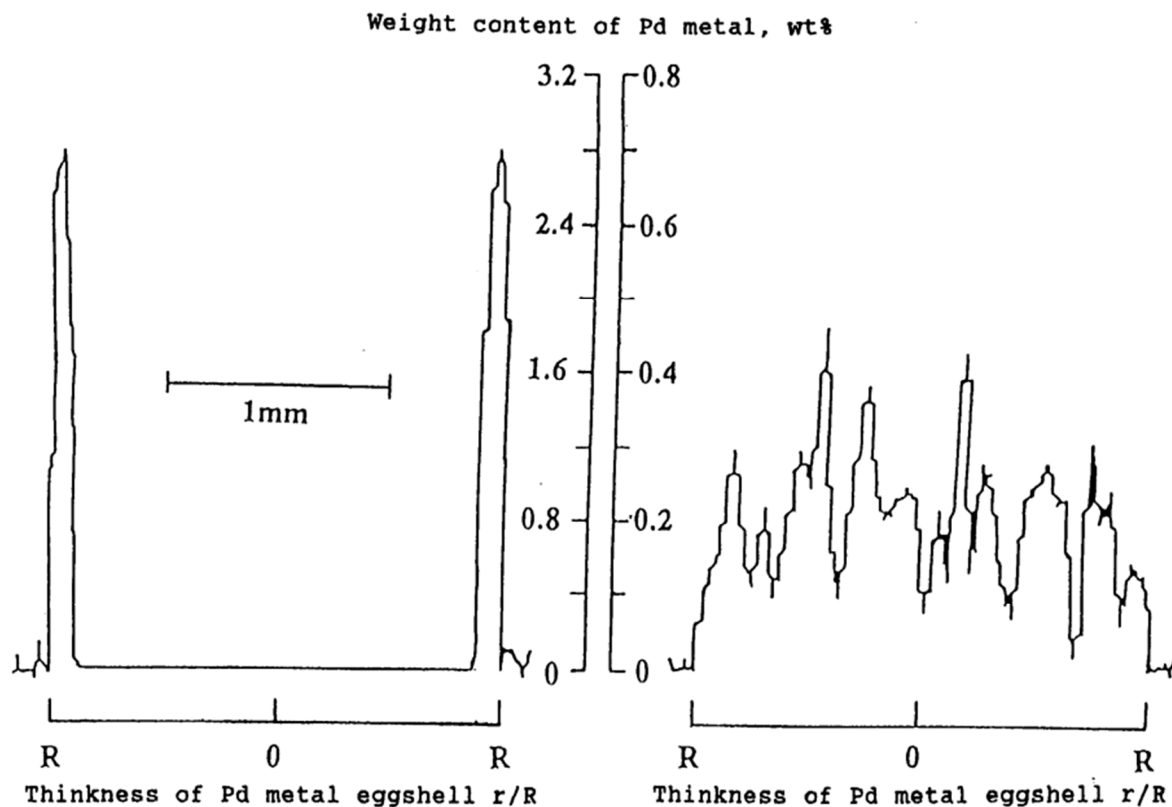


Fig.2

Fig.1

Id., 3-4, Fig. 1, Fig. 2. Therefore, a POSITA would have understood that the example disclosed in Lin demonstrates both a higher content (*i.e.*, mass) of active metal in the outer layer of the support and a higher concentration (*i.e.*, mass/volume) and/or weight percentage (*i.e.*, mass/mass)³ of active metal is present in the outer layer compared to the core. *Id.*

³ A POSITA would have recognized that concentration of noble metals is often given as wt.% which is effectively mass/total mass x 100. This is often called the metal loading. It is my understanding from the Prosecution History that the Patent Office defined concentration as “mass/volume.” See ’864 Prosecution History at 212. But I also understand that Patent Owner has asserted that concentration

(ii) Claim 2

[2] The combustion promoter according to claim 1, comprising a plurality of microsphere sized porous particles comprising silica.

215. In the Lin-Baker combination, Lin discloses the combustion promoter comprising a plurality of microsphere sized porous particles comprising silica. For example, Lin teaches an “eggshell metal catalyst” wherein the active metal is attached to a support comprising “*SiO₂*.” Lin, 3.

216. As I described above, Baker further discloses the combustion promoter comprising a plurality of microsphere sized porous particles comprising silica.

(iii) Claim 3

[3] The combustion promoter according to claim 1, comprising a plurality of microsphere sized porous particles comprising alumina.

217. In the Lin-Baker combination, Lin discloses the combustion promoter comprising a plurality of microsphere sized porous particles comprising alumina. For example, Lin discloses an “eggshell metal catalyst” wherein the active metal is attached to a support comprising “*Al₂O₃*.” Lin, 3. Lin further discloses “various non-uniformly distributed Pt on spherical *alumina support*.” *Id.*, 2. In addition,

means “mass per mass,” WRG-1016, which as I noted above would be a weight percent (mass/total mass x 100). Under either construction, it is my opinion that Lin discloses or renders obvious a higher concentration of the one or more Group VIII noble metals is present in the outer region of the microsphere sized porous particle as compared to the concentration of the one or more Group VIII noble metals in the centre of the microsphere sized porous particle.

Lin discloses an example wherein a “catalyst with linear decrease of Pd metal distribution from the outer layer toward the spherical core” comprises spherical γ - Al_2O_3 . *Id.*, 10.

218. As I described above, Baker further discloses the combustion promoter comprising a plurality of microsphere sized porous particles comprising alumina.

(iv) Claim 4

[4] The combustion promoter according to claim 1, comprising a first plurality of microsphere sized porous particles comprising silica and a second plurality of microsphere sized porous particles comprising alumina.

219. In the Lin-Baker combination, Lin discloses the combustion promoter comprising a first plurality of microsphere sized porous particles comprising silica and a second plurality of microsphere sized porous particles comprising alumina.

For example, Lin discloses an “eggshell metal catalyst” wherein the active metal is attached to a support comprising “ Al_2O_3 , SiO_2 . . . or the mixtures thereof.” Lin,

3. Lin further discloses “various non-uniformly distributed Pt on spherical

alumina support.” *Id.*, 2. In addition, Lin discloses an example wherein a

“catalyst with linear decrease of Pd metal distribution from the outer layer toward the spherical core” comprises spherical γ - Al_2O_3 . *Id.*, 10.

220. As I described above, Baker further discloses the combustion promoter comprising a first plurality of microsphere sized porous particles

comprising silica and a second plurality of microsphere sized porous particles comprising alumina.

(v) Claim 5

[5] The combustion promoter according to claim 1, comprising a plurality of microsphere sized porous particles comprising silica and alumina.

221. In the Lin-Baker combination, Lin discloses the combustion promoter comprising a plurality of microsphere sized porous particles comprising silica and alumina. For example, Lin discloses an “eggshell metal catalyst” wherein the active metal is attached to a support comprising “*Al₂O₃, SiO₂ . . . or the mixtures thereof.*” Lin, 3. Lin further discloses “various non-uniformly distributed Pt on spherical *alumina support.*” *Id.*, 2. In addition, Lin discloses an example wherein a “catalyst with linear decrease of Pd metal distribution from the outer layer toward the spherical core” comprises spherical γ -*Al₂O₃.* *Id.*, 10.

222. As I described above, Baker further discloses the combustion promoter comprising a plurality of microsphere sized porous particles comprising silica and alumina.

(vi) Claim 6

[6] The combustion promoter according to claim 1, wherein the microsphere sized porous particles collectively have an average (D50) size of between 60 and 90 microns as measured by laser diffraction.

223. In the Lin-Baker combination, and as I described above, Baker discloses the combustion promoter wherein the microsphere sized porous particles

collectively have an average (D50) size of between 60 and 90 microns as measured by laser diffraction.

(vii) Claim 7

[7] The combustion promoter according to claim 1, wherein the microsphere sized porous particles are gamma or theta alumina particles.

224. In the Lin-Baker combination, Lin discloses the combustion promoter wherein the microsphere sized porous particles are gamma or theta alumina particles. For example, Lin teaches an “eggshell metal catalyst” wherein the active metal is attached to a support comprising “*Al₂O₃*.” Lin, 3. Lin further discloses “various non-uniformly distributed Pt on spherical *alumina support*.” *Id.*, 2. In addition, Lin discloses an example wherein a “catalyst with linear decrease of Pd metal distribution from the outer layer toward the spherical core” comprises spherical *γ-Al₂O₃*. *Id.*, 10.

(viii) Claim 8

[8] The combustion promoter according to claim 1, wherein the microsphere sized porous particles are spray dried silica particles.

225. In the Lin-Baker combination, Lin discloses the combustion promoter wherein the microsphere sized porous particles are spray dried silica particles. For example, Lin teaches an “eggshell metal catalyst” wherein the active metal is attached to a support comprising “*SiO₂*.” Lin, 3. Lin further teaches that the active metal “is attached to a support by wet impregnation or *spray method*, in which the

support comprises Al_2O_3 , ***SiO***₂, zeolite, TiO_2 , ZrO_2 , MgO , active carbon, polymer or the mixtures thereof.” *Id.*

226. As I described above, Baker further discloses the combustion promoter wherein the microsphere sized porous particles are spray dried silica particles.

(ix) Claim 12

[12] The combustion promoter according to claim 1, wherein the one or more Group VIII noble metals comprises one or more of platinum, palladium, iridium, ruthenium, and rhodium.

227. In the Lin-Baker combination, Lin discloses the combustion promoter wherein the one or more Group VIII noble metals comprises one or more of platinum, palladium, iridium, ruthenium, and rhodium. Lin is directed to “an eggshell catalyst and process for preparation of the same,” including “single- or multiple-metal eggshell of the finished catalyst.” Lin, 1. Lin further teaches that the “eggshell” structure is known in the art as and discloses an eggshell catalyst wherein the “[m]etal is distributed on the outer layer of the support (with eggshell shape), which is usually used in fast reactions and capable of improving the selectivity and yield of the desired products.” *Id.*, 1-2. Lin teaches that the metal catalysts with eggshell active metal profile “preferably comprises ***Pd***, Ni, Co, Ho, Cu, ***Pt***, Fe, Ag, Tr, Pb, Re, Ti, Sn, V, and Zn, etc.” *Id.*, Abstract, 3.

228. As I described above, Baker further discloses the combustion promoter wherein the one or more Group VIII noble metals comprises one or more of platinum, palladium, iridium, ruthenium, and rhodium.

(x) Claim 13

[13] The combustion promoter according to claim 12, wherein the one or more Group VIII noble metals comprises platinum and palladium.

229. In the Lin-Baker combination, Lin discloses the combustion promoter wherein the one or more Group VIII noble metals comprises platinum and palladium. Lin is directed to “an eggshell catalyst and process for preparation of the same,” including “single- or multiple-metal eggshell of the finished catalyst.” Lin, 1. Lin further teaches that the “eggshell” structure is known in the art as and discloses an eggshell catalyst wherein the “[m]etal is distributed on the outer layer of the support (with eggshell shape), which is usually used in fast reactions and capable of improving the selectivity and yield of the desired products.” *Id.*, 1-2. Lin teaches that the metal catalysts with eggshell active metal profile “preferably comprises ***Pd***, Ni, Co, Ho, Cu, ***Pt***, Fe, Ag, Tr, Pb, Re, Ti, Sn, V, and Zn, etc.” *Id.*, Abstract, 3.

230. As I described above, Baker further discloses the combustion promoter wherein the one or more Group VIII noble metals comprises platinum and palladium.

(xi) Claim 14

[14] The combustion promoter according to claim 12, wherein the one or more Group VIII noble metals comprises platinum.

231. In the Lin-Baker combination, Lin discloses the combustion promoter wherein the one or more Group VIII noble metals comprises platinum. Lin is directed to “an eggshell catalyst and process for preparation of the same,” including “single- or multiple-metal eggshell of the finished catalyst.” Lin, 1. Lin further teaches that the “eggshell” structure is known in the art as and discloses an eggshell catalyst wherein the “[m]etal is distributed on the outer layer of the support (with eggshell shape), which is usually used in fast reactions and capable of improving the selectivity and yield of the desired products.” *Id.*, 1-2. Lin teaches that the metal catalysts with eggshell active metal profile “preferably comprises Pd, Ni, Co, Ho, Cu, **Pt**, Fe, Ag, Tr, Pb, Re, Ti, Sn, V, and Zn, etc.” *Id.*, Abstract, 3.

232. As I described above, Baker further discloses the combustion promoter wherein the one or more Group VIII noble metals comprises platinum.

(xii) Claim 15

[15] The combustion promoter according to claim 12, wherein the one or more Group VIII noble metals comprises palladium.

233. In the Lin-Baker combination, Lin discloses the combustion promoter wherein the one or more Group VIII noble metals comprises palladium. Lin is directed to “an eggshell catalyst and process for preparation of the same,”

including “single- or multiple-metal eggshell of the finished catalyst.” Lin, 1. Lin further teaches that the “eggshell” structure is known in the art as and discloses an eggshell catalyst wherein the “[m]etal is distributed on the outer layer of the support (with eggshell shape), which is usually used in fast reactions and capable of improving the selectivity and yield of the desired products.” *Id.*, 1-2. Lin teaches that the metal catalysts with eggshell active metal profile “preferably comprises ***Pd***, Ni, Co, Ho, Cu, Pt, Fe, Ag, Tr, Pb, Re, Ti, Sn, V, and Zn, etc.” *Id.*, Abstract, 3.

234. As I described above, Baker further discloses the combustion promoter wherein the one or more Group VIII noble metals comprises palladium.

(xiii) Claim 16

[16] The combustion promoter according to claim 1, wherein the microsphere sized porous particles further comprise at least one of cerium oxide and copper oxide.

235. In the Lin-Baker combination, Lin discloses the combustion promoter according to claim 1, wherein the microsphere sized porous particles further comprise at least one of cerium oxide and copper oxide. Lin is directed to “an eggshell catalyst and process for preparation of the same,” including “single- or multiple-metal eggshell of the finished catalyst.” Lin, 1. Lin further teaches that the “eggshell” structure is known in the art as and discloses an eggshell catalyst wherein the “[m]etal is distributed on the outer layer of the support (with eggshell

shape), which is usually used in fast reactions and capable of improving the selectivity and yield of the desired products.” *Id.*, 1-2. Lin teaches that the metal catalysts with eggshell active metal profile “preferably comprises Pd, Ni, Co, Ho, **Cu**, Pt, Fe, Ag, Tr, Pb, Re, Ti, Sn, V, and Zn, etc.” *Id.*, Abstract, 3. Lin further teaches that **copper nitrate** ($\text{Cu}(\text{NO}_3)_2$) is “used by means of various impregnation technologies to produce **non-uniformly distributed** Cr and **Cu metal in different state** on spherical Al_2O_3 support.” *Id.*, 2. A POSITA would understand the similar properties of copper oxide and copper nitrate, as taught by Lin, in application to catalytic reactions. Thereby, a POSITA would easily substitute copper oxide for copper nitrate. *Id.* Moreover, a POSITA would understand that copper is easily oxidized when exposed to air and therefore the “Cu metal in different states on spherical Al_2O_3 support” may include copper metal naturally oxidized. *Id.*

236. As I described above, Baker further discloses the combustion promoter according to claim 1, wherein the microsphere sized porous particles further comprise at least one of cerium oxide and copper oxide.

(xiv) Claim 17

[17] The combustion promoter according to claim 16, wherein the at least one of cerium oxide and copper oxide is distributed in the microsphere sized porous particle as an eggshell such that a higher concentration of the at least one of cerium oxide and copper oxide is present in the outer region of the microsphere sized porous particle as compared to the concentration of the at least one of cerium oxide and copper oxide in the centre of the microsphere sized porous particle.

237. In the Lin-Baker combination, Lin discloses the combustion promoter wherein the at least one of cerium oxide and copper oxide is distributed in the microsphere sized porous particle as an eggshell such that a higher concentration of the at least one of cerium oxide and copper oxide is present in the outer region of the microsphere sized porous particle as compared to the concentration of the at least one of cerium oxide and copper oxide in the center of the microsphere sized porous particle. As shown above, Lin further teaches that the “eggshell” structure is known in the art as and discloses an eggshell catalyst wherein the “[m]etal is distributed on the outer layer of the support (with eggshell shape), which is usually used in fast reactions and capable of improving the selectivity and yield of the desired products.” *Id.*, 1-2. Lin teaches that the metal catalysts with eggshell active metal profile “preferably comprises Pd, Ni, Co, Ho, **Cu**, Pt, Fe, Ag, Tr, Pb, Re, Ti, Sn, V, and Zn, etc.” *Id.*, Abstract, 3. Lin further teaches that **copper nitrate** ($\text{Cu}(\text{NO}_3)_2$) is “used by means of various impregnation technologies to produce **non-uniformly distributed** Cr and **Cu metal in different state** on spherical Al_2O_3 support.” *Id.*, 2. A POSITA would have understood the similar properties of copper oxide and copper nitrate, as taught by Lin, in application to catalytic reactions. Thereby, a POSITA would have easily substituted copper oxide for copper nitrate. *Id.* Moreover, a POSITA would have understood that copper is oxidized easily when exposed to air and therefore the “Cu metal in different states

on spherical Al_2O_3 support” may include copper metal naturally oxidized. *Id.* This non-uniform distribution of copper metal results in the disclosed eggshell-shaped catalyst of Lin.

(xv) **Claim 18⁴**

[18pre] The combustion promoter according to claim 1, obtained by a process comprising the following steps:

238. To the extent the preamble is limiting, in the Lin-Baker combination, Lin discloses the preamble. Lin teaches that “eggshell catalysts have been widely employed in the industrially selective hydrogenation” and, in particular, discloses “*a process for the preparation of an eggshell-shaped catalyst* for use in selective reduction or oxidation,” including, for example, oxidation of CO. *Id.*, 1-2, 13.

[18a] introducing a medium in the pores of microsphere sized porous particles having a diameter of less than 1 mm to obtain microsphere sized porous particles with filled pores; and

239. Lin-Baker renders obvious introducing a medium in the pores of microsphere sized porous particles having a diameter of less than 1 mm to obtain microsphere sized porous particles with filled pores. Lin teaches that “eggshell catalysts have been widely employed in the industrially selective hydrogenation” and, in particular, discloses “an eggshell-shaped catalyst for use in selective

⁴ Lin-Baker renders obvious claim 18 because the combination renders obvious claim 1. *See* MPEP § 2113.

reduction or oxidation,” including, for example, oxidation of CO. Lin, 1-2, 13.

Lin further teaches an example wherein a catalyst was prepared using “spherical particles with diameter of 2mm.” *Id.*, 5. Lin further discloses a process for preparing a catalyst with linear decrease of Pd metal distribution from the outer layer toward the spherical core wherein the first step is dissolving an aqueous salt in deionized water and placing “spherical $\gamma\text{-Al}_2\text{O}_3$ ” in the solution. *Id.*, 10.

240. As discussed above, Baker also discloses “catalyst composition comprising support particles having at least one catalytically active metal distributed therein” wherein the “catalyst composition [is] suitable for the manufacture of vinyl acetate may also comprise . . . promoters.” Baker, 1:60-67, 4:66-5:12. Baker further teaches support particles that are “microspheroidal,” and have an average particle size of approximately 73 microns. *Id.*, 1:60-67, 3:16-46. Baker further discloses that the “catalytically active metal(s) may be impregnated in one or more steps onto the support particles in the form of precursor salt solutions” wherein the preferably medium is a palladium compound in a suitable solvent, such as water, carboxylic acids, alcohols, nitriles, or chlorinated solvents. *Id.*, 4:48-65.

241. A POSITA would have been motivated to use the particles less than 1mm, as disclosed by Baker, to prepare an eggshell-shaped catalyst, as described by Lin, in light of the small (2mm) particle size disclosed by Lin. For example, a

POSITA would have recognized that the difference in size from 1mm to 2mm is not significant, in particular, because it was well known in the art to use particle sizes ranging by order of magnitude, as evidenced by the complete range of the microsphere sized particles as defined by the '864 Patent (*i.e.*, 1mm to zero). *Id.*

[18b] contacting the microsphere sized porous particles with filled pores with an aqueous salt solution of the one or more Group VIII noble metals,

242. In the Lin-Baker combination, Lin discloses contacting the microsphere sized porous particles with filled pores with an aqueous salt solution of the one or more Group VIII noble metals. Lin teaches discloses a process for preparing a catalyst with linear decrease of Pd metal distribution from the outer layer toward the spherical core wherein the first step is dissolving an *aqueous salt solution—Ni(NO₂)₂·6H₂O*—with a Group VIII noble metal, nickel, in deionized water and placing “spherical γ -Al₂O₃” in the solution. Lin, 10.

243. As I described above, Baker further discloses contacting the microsphere sized porous particles with filled pores with an aqueous salt solution of the one or more Group VIII noble metals.

[18c] wherein the one or more Group VIII noble metals deposits at a higher content in the outer region of the microsphere sized porous particles with filled pores as compared to the content of the one or more Group VIII noble metals in the centre of the microsphere sized porous particles with filled pores, thereby obtaining eggshell particles.

244. In the Lin-Baker combination, Lin discloses wherein the one or more Group VIII noble metals deposits at a higher content in the outer region of the

microsphere sized porous particles with filled pores as compared to the content of the one or more Group VIII noble metals in the centre of the microsphere sized porous particles with filled pores, thereby obtaining eggshell particles. Lin teaches discloses a process for preparing a catalyst with linear decrease of Pd metal distribution from the outer layer toward the spherical core wherein the first step is dissolving an aqueous salt solution— $\text{Ni}(\text{NO}_2)_2 \cdot 6\text{H}_2\text{O}$ —with a Group VIII noble metal, nickel, in deionized water and placing “spherical $\gamma\text{-Al}_2\text{O}_3$ ” in the solution. Lin, 10. Lin teaches the second step as placing the resulting catalyst sample “in a solution of over-saturated $\text{Pd}(\text{CH}_3\text{COO})_2$ /toluene and treated by wet impregnation for 0.5 hour” and then “filtering and drying at 110°C for 1 hour.” *Id.* Lastly, Lin teaches analyzing the resulting catalyst sample to determine the distribution of palladium such that “[o]bviously, the Pd metal distribution exhibits a linear decrease from outer layer toward spherical core.” *Id.*; see also *id.*, FIG 17.

(xvi) Claim 19

[19] The combustion promoter of claim 18, the process further comprising a step: (c) at least one of drying and calcining the eggshell particles.

245. In the Lin-Baker combination, Lin discloses at least one of drying and calcining the eggshell particles. Lin teaches discloses a process for preparing a catalyst with linear decrease of Pd metal distribution from the outer layer toward the spherical core wherein the first step is dissolving an aqueous salt solution— $\text{Ni}(\text{NO}_2)_2 \cdot 6\text{H}_2\text{O}$ —with a Group VIII noble metal, nickel, in deionized water and

placing “spherical γ - Al_2O_3 ” in the solution. Lin, 10. Lin teaches the second step as placing the resulting catalyst sample “in a solution of over-saturated $\text{Pd}(\text{CH}_3\text{COO})_2$ /toluene and treated by wet impregnation for 0.5 hour” and then “filtering and drying at 110°C for 1 hour.” *Id.*

246. As I described above, Baker further discloses at least one of drying and calcining the eggshell particles.

(xvii) Claim 20

[20] The combustion promoter according to claim 18, wherein the microsphere sized porous particles having pores filled in step (a) are gamma alumina particles having an average (D50) size of between 60 and 90 microns, have a surface area (BET) of between 50 and 300 m^2/g , and a pore volume of between 0.05 and 0.50 mL/g as measured by the water pore volume.

247. Lin-Baker renders obvious the microsphere sized porous particles having pores filled in step (a) are gamma alumina particles having an average (D50) size of between 60 and 90 microns, have a surface area (BET) of between 50 and 300 m^2/g , and a pore volume of between 0.05 and 0.50 mL/g as measured by the water pore volume. First, Lin-Baker teaches the claimed particles. Lin discloses an example wherein a “catalyst with linear decrease of Pd metal distribution from the outer layer toward the spherical core” comprises spherical γ - Al_2O_3 . Lin, 10. Lin further teaches using “spherical particles with diameter of 2mm.” *Id.*, 5. Baker specifically teaches that the catalyst has the following particle size distribution:

0 to 20 microns	0-30 wt %
20 to 44 microns	0-60 wt %
44 to 88 microns	10-80 wt %
88 to 106 microns	0-80 wt %
>106 microns	0-40 wt %
>300 microns	0-5 wt %

Baker, 3:16-33, wherein the average particle size is approximately 73 microns. Baker therefore teaches an average (D50) size of between 60 and 90 microns. A POSITA would have understood that the γ -alumina particles with an average particle size between 60 and 90 microns may be used. Namely, Lin teaches the use of γ -alumina particles and using small (2mm) particles in an eggshell catalyst. Lin, 10. Thus, a POSITA would have been motivated to combine the small γ -alumina particles, as described by Lin, with the average particles size disclosed by Baker. For example, a POSITA would have recognized that the difference in size from 1mm to 2mm is not significant, in particular, because it was well known in the art to use particle sizes ranging by order of magnitude, as evidenced by the complete range of the microsphere sized particles as defined by the '864 Patent (i.e., 1mm to zero). *Id.*

248. Second, Lin discloses the claimed surface area. Lin discloses “spherical particles with diameter of 2mm, surface area of 82.4 m²/g”. Lin, 5, 10. Therefore, a POSITA would have recognized that Lin teaches an overlap of the claimed surface area. Moreover, Baker also discloses the claimed surface area. Baker discloses the surface area of support particles is typically “about 50 m²/g and

may range up to about 200 m²/g . . . and may range up to about 800 m²/g.” Baker, 3:41-51, 4:18-28. Therefore, a POSITA would have recognized that Baker likewise teaches an overlap of the claimed surface area.

249. Third, Baker discloses the claimed pore volume. Baker discloses that a “typically suitable microspheroidal support particle has a pore volume (measured by nitrogen sorption) between about 0.2 and 0.7 cc/g.” *Id.*, 3:41-51, 4:18-28. A POSITA would understand that the volume measurement cc/g is equivalent to mL/g. Therefore, a POSITA would have recognized that Baker teaches an overlap of the claimed pore volume.

(xviii) Claim 21

[21] The combustion promoter according to claim 18, wherein the medium in step (a) is water.

250. In the Lin-Baker combination, Lin discloses the medium in step (a) is water. For example, Lin teaches an “eggshell metal catalyst” wherein the active metal “is attached to a support by *wet impregnation* or spray method, in which the support comprises Al₂O₃, SiO₂, zeolite, TiO₂, ZrO₂, MgO, active carbon, polymer or the mixtures thereof.” Lin, 3. As another example, Lin teaches discloses a process for preparing a catalyst with linear decrease of Pd metal distribution from the outer layer toward the spherical core wherein the first step is dissolving an aqueous salt solution—Ni(NO₂)₂·6H₂O—with a Group VIII noble metal, nickel, *in deionized water* and placing “spherical γ-Al₂O₃” in the solution. *Id.*, 10.

251. As I described above, Baker further discloses the medium in step (a) is water.

(xix) Claim 22

[22] The combustion promoter according to claim 18, wherein in step (b) the filled microsphere sized porous particles are contacted in step (b) with a volume of the aqueous salt solution of the one or more Group VIII noble metals which is less than the total volume of the pores of the starting microsphere sized particles.

252. In the Lin-Baker combination, and as I described above, Baker discloses in step (b) the filled microsphere sized porous particles are contacted in step (b) with a volume of the aqueous salt solution of the one or more Group VIII noble metals which is less than the total volume of the pores of the starting microsphere sized particles.

O. [GROUND 3A] – CLAIM 9 IS OBVIOUS OVER LIN IN VIEW OF BAKER AND IN FURTHER VIEW OF VAUGHN 290

253. It is my opinion that a POSITA would have found claim 9 to be obvious over Lin and Baker and in further view of Vaughn 290, as I discuss in the following sections.

1. Combination of Lin, Baker, and Vaughn 290

254. As described above, Lin discloses “an eggshell catalyst and process for preparation of the same,” including “single- or multiple-metal eggshell of the finished catalyst” wherein the “[m]etal is distributed on the outer layer of the support (with eggshell shape), which is usually used in fast reactions and capable

of improving the selectivity and yield of the desired products.” Lin, 1-2.

Similarly, Baker discloses a non-uniform structure similar to that of Lin, wherein the “catalyst composition comprising support particles hav[e] at least one catalytically active metal distributed therein” wherein the “catalyst composition [is] suitable for the manufacture of vinyl acetate may also comprise . . .

promoters.” Baker, 1:60-67, 4:66-5:12. Vaughn 290, similar to Lin and Baker, discloses a catalyst which contains molecular sieve-containing attrition particles and virgin molecular sieve, the attrition particles having been recycled from a catalyst manufacture process or from a reaction system.” Vaughn 290, 1:7-13.

Vaughn 290 further teaches that the disclosed catalyst may be used in a variety of catalytic reaction processes such that the recycled catalyst particles can be used to form a catalytic composition. *Id.*, Abstract, 2:43-45. A POSITA would have recognized the variety of catalytic reaction processes as including a CO to CO₂ combustion promoter. In addition, Vaughn 290 discloses ***recycled*** particles that “are actually molecular sieve-containing catalyst particles that have been [sic] used in a functioning manufacture or reaction system, and have been reduced in size due to attrition.” *Id.*, 9:55-65. Thus, Vaughn 290 discloses that the “catalyst fines are recovered from the manufacture or reaction system and are recycled back into the catalyst manufacturing scheme. The catalyst fines, therefore, are incorporated into the finished catalyst particles.” Vaughn 290, 9:55-65, 16:26-35; While Lin-Baker

does not disclose an equilibrium or spent catalyst, a POSITA would understand that “the recovery and use of the attrition particles in [a] catalyst is beneficial in minimizing waste, thereby reducing problems relating to both environmental and economic constraints.” Vaughn 290, Abstract.

255. By incorporating the recycling teachings of Vaughn 290 into Lin-Baker, a POSITA would have recognized the efficiencies and benefits of recycling catalyst material in combination with Lin’s and/or Baker’s non-uniform catalyst. Indeed, Vaughn 290 teaches that “the recovery and use of the attrition particles in [a] catalyst is beneficial in minimizing waste, thereby reducing problems relating to both environmental and economic constraints.” Vaughn 290, Abstract. Lin discloses the metal catalysts with eggshell active metal profile “preferably comprises Pd, Ni, Co, Ho, Cu, Pt, Fe, Ag, Tr, Pb, Re, Ti, Sn, V, and Zn, etc.” Lin, Abstract, 3. Baker likewise teaches depositing noble metals, such as “palladium, platinum, rhodium, ruthenium, osmium and iridium,” in a *non-uniform* particle wherein the concentration of noble metal is lowest at the center “inner region” of the particle. Baker, FIG 1, 1:60-67, 4:39-47, 7:35-53. A POSITA would have recognized the expense of the noble metals disclosed in Lin and Baker and appreciate the cost-saving efficiencies that both teach by depositing the noble metal on the surface or outer edge of the particle, rather than uniformly distributed throughout the particles. This cost-saving measure of Lin and Baker would have

motivated a POSITA to apply additional efficiencies to the preparation of the catalyst particles, namely the recycling process disclosed by Vaughn 290.

256. A POSITA would have been further prompted to pursue the efficiencies of Vaughn 290 as doing so is merely the application of known techniques (*e.g.*, recycling combustion promoter particles) to a known structure (*e.g.*, the combustion promoter particles) to yield predictable results (*e.g.*, minimizing waste). And a POSITA would have expected success in the Lin-Baker-Vaughn 290 combination given that each reference describes catalyst for use in a variety of catalytic reaction processes, including well-known CO to CO₂ combustion promotion process. *See* Lin, 1-2; Baker, 1:60-67, 4:66-5:12; Vaughn 290, Abstract, 2:43-45.

2. Analysis

(i) Claim 9

[9] The combustion promoter according to claim 1, wherein the microsphere sized porous particles are an equilibrium or spent catalyst as obtained from a fluidized catalytic cracking (FCC) process.

257. Lin-Baker-Vaughn 290 renders obvious claim 9. As discussed above, Lin-Baker renders obvious claim 1. Further, as discussed above, Vaughn 290 renders obvious an equilibrium or spend catalyst.

P. [GROUND 3B] – CLAIMS 10 & 11 ARE OBVIOUS OVER LIN IN VIEW OF BAKER AND IN FURTHER VIEW OF PETERS OR, ALTERNATIVELY, VAUGHN 516

258. It is my opinion that a POSITA would have found claims 10 and 11 to be obvious over Lin and Baker and in further view of Peters or, alternatively, Vaughn 516, as I discuss in the following sections.

1. Combination of Lin, Baker, and Peters

259. It is my opinion that a POSITA would have recognized the attrition value of catalyst particles, such as those described by Peters, to the eggshell catalyst particles disclosed in Lin-Baker and would have been motivated to combine the two references for at least the reasons I discuss below.

260. As described above, Lin discloses “an eggshell catalyst and process for preparation of the same,” including “single- or multiple-metal eggshell of the finished catalyst” wherein the “[m]etal is distributed on the outer layer of the support (with eggshell shape), which is usually used in fast reactions and capable of improving the selectivity and yield of the desired products.” Lin, 1-2. Similarly, Baker discloses a non-uniform structure similar to that of Lin, wherein the “catalyst composition comprising support particles hav[e] at least one catalytically active metal distributed therein” wherein the “catalyst composition [is] suitable for the manufacture of vinyl acetate may also comprise . . . promoters.” Baker, 1:60-67, 4:66-5:12. However, neither Lin nor Baker expressly

discloses an attrition index of the metal oxide particles, though a POSITA would have understood that catalyst material should be durable and attrition-resistant and therefore a low attrition index is desirable, while reducing NO_x emissions. Peters, similar to Lin, discloses “compositions suitable for use in FCC processes which are capable of promoting CO combustion while avoiding significant NO_x formation.” Peters, 1:49-60. Lin, Baker, and Peters teach the use of similar components of the combustion promoter, namely, the use of ceria or copper as the preferred oxide component as the outer layer (most susceptible to attrition) of the eggshell structure disclosed by Lin. *See* Lin, Abstract, 2, 3; Baker, 4:8-36, 4:66-5:12; Peters, 1:49-60. A POSITA would have understood the similar properties of cerium oxide and copper oxide in application to catalytic reactions. While Lin-Baker is silent as to the attrition index, Peters explicitly identifies the attrition index value of the combustion promoter composition. Peters, 3:9-20.

261. A POSITA would have understood that Lin teaches the use of copper as the outer portion of the particle and, thus, the surface layer most susceptible to attrition. Lin discloses “an eggshell catalyst and process for preparation of the same,” including “single- or multiple-metal eggshell of the finished catalyst.” Lin, 1. Lin further teaches that the “eggshell” structure is known in the art as and discloses an eggshell catalyst wherein the “[m]etal is distributed on the outer layer of the support (with eggshell shape), which is usually used in fast reactions and

capable of improving the selectivity and yield of the desired products.” *Id.*, 1-2.

Lin teaches that the metal catalysts with eggshell active metal profile “preferably comprises Pd, Ni, Co, Ho, **Cu**, Pt, Fe, Ag, Tr, Pb, Re, Ti, Sn, V, and Zn, etc.” *Id.*, Abstract, 3. Lin further teaches that **copper nitrate** ($\text{Cu}(\text{NO}_3)_2$) is “used by means of various impregnation technologies to produce **non-uniformly distributed** Cr and **Cu metal in different state** on spherical Al_2O_3 support.” *Id.*, 2. A POSITA would have understood the similar properties of copper oxide and copper nitrate, as taught by Lin, in application to catalytic reactions. Thereby, a POSITA would have easily substituted copper oxide for copper nitrate. Moreover, a POSITA would have understood that copper is oxidized easily when exposed to air and therefore the “Cu metal in different states on spherical Al_2O_3 support” may include copper metal naturally oxidized. This non-uniform distribution of copper metal results in the disclosed eggshell-shaped catalyst of Lin. A POSITA would have understood that copper and ceria have similar properties of microhardness and wear resistance. A POSITA would thereby have understood the disclosure of Lin would have similar attrition properties to the value disclosed by Peters where Peters likewise teaches the use of similar metal oxide as a component of the catalyst particle.

262. By incorporating the specific attrition index teachings of Peters to Lin-Baker, a POSITA would have recognized that the attrition index value of Lin-Baker, using cerium oxide or copper oxide as the outer layer of the combustion

particles, would have been similar or equivalent to the values disclosed in Peters. A POSITA would have been further prompted to pursue the optimal attrition index of the combustion promoter particles as doing so is merely the application of known techniques (*e.g.*, standard attrition measurement) to a known structure (*e.g.*, the combustion promoter particles) to yield predictable results (*e.g.*, improved attrition properties). '864 patent, 6:53-63. And a POSITA would have expected success in the Lin-Baker-Peters combination given that both Lin and Baker already describe using cerium oxide or copper oxide as the metal oxide component of the combustion promoter. *See* Lin, Abstract, 2, 3; Peters, 1:49-60.

2. Combination of Lin, Baker, and Vaughn 516

263. It is my opinion that a POSITA would have recognized the attrition value of catalyst particles, such as those described by Vaughn 516, to the eggshell catalyst particles disclosed in Lin-Baker and would have been motivated to combine the two references for at least the reasons I discuss below.

264. As described above, a POSITA would have been motivated to combine Lin and Baker. Likewise, a POSITA would have been motivated to combine Vaughn 516. Vaughn 516 is directed to processes for removing undesirably sized catalyst particles from a catalyst synthesis system; in particular, Vaughn 516 discloses a molecular sieve to obtain a slurry of optimally-sized catalyst particles. Vaughn 516, Abstract. Vaughn 516 teaches that the benefit of

the disclosed processes is to obtain a formulated catalyst mixture with desirable catalytic activity characteristics for use in a reaction system. *Id.*

265. Similar to Lin and Baker, *see* Lin, Abstract, 2, 3; Baker, 4:8-36, 4:66-5:12, Vaughn 516 teaches the use of similar components of the catalyst particles, namely, the matrix or support material contains alumina or silica. *See* Lin, 1-3; Baker, 1:60-67, 4:8-36; Vaughn 516, [0085]. Likewise, Vaughn 516, similar to Lin and Baker, teaches the use of Group VIII metals, including platinum and palladium, as reactive components of the catalytic particle. Vaughn 516, [0108], [0164]; Lin, 1-3; Baker, 1:60-67, 4:39-47. A POSITA would have understood the similar properties of platinum and/or palladium in application to catalytic reactions. While Lin-Baker is silent as to the attrition index, Vaughn 516 explicitly identifies the attrition index value of the combustion promoter composition. Vaughn 516, [0131]. A POSITA would have understood that catalyst material should be durable and attrition-resistant and therefore a low attrition index is desirable, while reducing NO_x emissions.

266. A POSITA would have understood that Lin teaches a low concentration of noble metal in the core of the particle. Lin discloses “an eggshell catalyst and process for preparation of the same,” including “single- or multiple-metal eggshell of the finished catalyst.” Lin, 1. Lin further teaches that the “eggshell” structure is known in the art as and discloses an eggshell catalyst

wherein the “[m]etal is distributed on the outer layer of the support (with eggshell shape), which is usually used in fast reactions and capable of improving the selectivity and yield of the desired products.” *Id.*, 1-2. Lin teaches that the metal catalysts with eggshell active metal profile “preferably comprises ***Pd***, Ni, Co, Ho, Cu, Pt, Fe, Ag, Tr, Pb, Re, Ti, Sn, V, and Zn, etc.” *Id.*, Abstract, 3. This non-uniform distribution of noble metal results in the disclosed eggshell-shaped catalyst of Lin. Likewise, Vaughn 516, similar to Lin and Baker, teaches the use of Group VIII metals, including platinum and palladium, such that the concentration of the Group VIII metal is low in the support material. Vaughn 516, [0108], [0164]; Miura, [[0048], [0072], Fig. 2]. Vaughn 516 specifically teaches that this design choice is effective in reducing overall catalyst cost and “increasing catalyst strength such as crush strength and attrition resistance.” Vaughn 516, [0106]. A POSITA would thereby have understood the disclosure of Lin would have similar attrition properties to the value disclosed by Vaughn 516 where Vaughn 516 likewise teaches the use of catalytic components with similar distribution within the catalyst particle.

267. By incorporating the specific attrition index teachings of Vaughn 516 to Lin-Baker, a POSITA would have recognized that the attrition index value of Lin-Baker, using components with similar distribution within the combustion particles, would have been similar or equivalent to the values disclosed in Vaughn

516. A POSITA would have been further prompted to pursue the optimal attrition index of the combustion promoter particles as doing so is merely the application of known techniques (*e.g.*, standard attrition measurement) to a known structure (*e.g.*, the combustion promoter particles) to yield predictable results (*e.g.*, improved attrition properties). '864 patent, 6:53-63. And a POSITA would have expected success in the Lin-Baker-Vaughn 516 combination given that both already describe using catalytic components with similar distribution within the combustion promoter. *See* Lin, 1-3; Baker, 1:60-67, 4:39-47; Vaughn 516, [0086].

3. Analysis

(i) Claim 10

[10] The combustion promoter according to claim 1, wherein the attrition index as measured according to ASTM D-5757 of the CO to CO₂ combustion promoter for a sieve fraction of combustion promoter particles of between 40 and 105 microns is between 5 and 25.

268. Lin-Baker-Peters or, alternatively, Lin-Baker-Vaughn 516 renders obvious claim 10. As discussed above, Lin-Baker renders obvious claim 1. Further, as discussed above, Peters or Vaughn 516 renders obvious particle size between 40 and 105 microns with an attrition index between 5 and 25.

(ii) Claim 11

[11] The combustion promoter according to claim 10, wherein the attrition index of the CO to CO₂ combustion promoter for a sieve fraction of combustion promoter particles of between 40 and 105 microns is between 10 and 20.

269. Lin-Baker-Peters or, alternatively, Lin-Baker-Vaughn 516 renders obvious claim 11. As discussed above, Lin-Baker renders obvious claim 1. Further, as discussed above, Peters or Vaughn 516 renders obvious particle size between 40 and 105 microns with an attrition index between 10 and 20.

Q. [GROUND 4] – CLAIMS 1-4, 6, 12-15, 18, 19, 21, 22 ARE OBVIOUS IN VIEW OF ESPINOZA IN VIEW OF AAPA

270. It is my opinion that a POSITA would have found claims 1-4, 6, 12-15, 18, 19, 21, and 22 to be obvious over Espinoza and AAPA, as I discuss in the following sections.

1. Overview of Espinoza

271. Espinoza is directed to a catalyst comprising an inner core and outer layer wherein the outer layer contains catalytically active metal, such as a Group VIII metal, which is *not* deposited in the core of the particle. Espinoza, 4:26-47. Espinoza teaches that the cost efficiency of loading the catalytically active metal on the outer layer of the particle and identifies that “uniform dispersion inherently exiles a substantial amount of catalytic metal to the deep internal surfaces or ‘core’ of a support.” *Id.*, 2:37-44.

272. Espinoza further teaches that “[t]he present invention is directed towards improved catalyst systems, as well as methods of making and using such systems. The present invention provides a syngas catalyst system comprising a core and an outer layer comprising a catalytically active metal, in which effective

use of the catalyst metal is enhanced and the occurrence of undesirable secondary reactions is inhibited. The invention achieves this result by minimizing diffusion of the reactant gases into the core of the catalyst particle. Thus, the reactant gases are not allowed to linger in the particle core and react unfavorably, and *the expensive catalytically active materials are only placed where their presence is most economically beneficial.*” *Id.*, 3:49-4:4.

273. Espinoza further teaches that “[t]he present invention further relates to methods for preparing catalyst compositions in accordance with the present invention. For example, a method for preparing nonmicroporous catalyst particles, each having a core comprising a refractory support like alumina or zirconia and an outer layer, includes applying a pore blocking material such as silicic acid or sodium carbonate to the support material, so as to substantially block the micropores of the support material and obtain a nonmicroporous core of the catalyst particle. The particles are then provided a catalytically active material for catalyzing reactions, *wherein the catalytically active material preferably comprises a Group VIII metal like rhodium and optionally a promoter metal such as a lanthanide metal or rhenium, dispersed in the outer layer, wherein the catalytically active material does not substantially penetrate and deposit into the core because of the blocked pores.* Another embodiment involves preparing catalysts using an impregnation technique employing a fast drying or low vapor

pressure solvent, which allows preferential deposition of the active material in an outer layer, preferably deposited on the outer surface of the support.” *Id.*, 4:26-47.

274. Espinoza further teaches that “[o]ne embodiment of the present invention is for a catalyst system in which the majority of the catalytic metal is near the surface of the support matrix. In other words, the catalyst is not uniformly dispersed throughout the catalyst matrix, but instead has regions of differing catalyst concentration. For example, as shown in FIG. 1, the support could have more than one discrete region comprising differing catalyst concentrations.” *Id.*, 5:52-6:23.

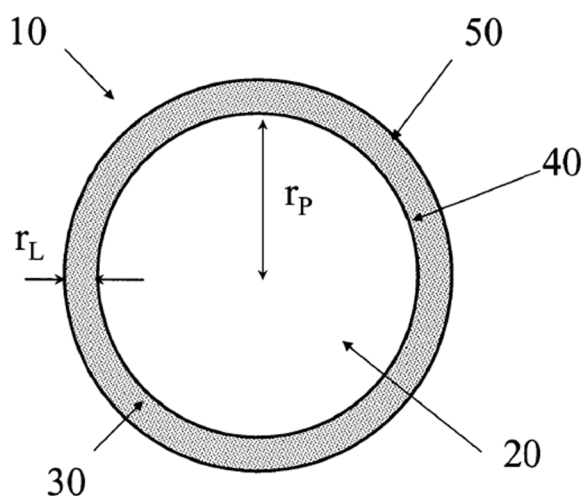


Figure 1

275. Continuing, Espinoza discloses that “[a]s shown, the spherical catalyst system 10 has two regions 20 and 30. Region 20 is the inner core, and region 30, also called outer layer, is the area at the periphery of the core. Region 30 is delimited by exterior surface 50 of catalyst system 10 and outer surface 40 of the

region 20. In the broadest and simplest terms and in accordance with the present invention, ***region 20 should have a lower amount of catalyst than region 30.*** In other words, the catalyst material should be distributed such that if region 20 and 30 were divided into two sections of equal volume, i.e., 50-50, ***more than 50% of the catalytically active material would be located in region 30.*** In a preferred embodiment, ***region 20 would comprise substantially lower amounts of catalyst than region 30.*** The general objective being that more than 50% of the catalytically active material is located in a contiguous region of the support that comprises 50% or less of the total support volume. ***In a more preferred embodiment, region 20 would have substantially zero catalytic material.”*** *Id.*, 5:52-6:23.

276. Espinoza further teaches that “[i]n another embodiment of the present invention shown in FIG. 2, a catalyst particle 110 has a core 120 with an outer surface 140, a catalytic outer layer 130 with an exterior surface 150, and a substantially blocked-micropore layer 135. The substantially blocked-micropore layer 135 ***substantially prevents access to deposition of catalytic material in internal surface of core 120 of the catalyst particle 110. Thus, catalyst material are deposited primarily only on the outer surface 140 of the core 120 and form the outer layer 130.*** The substantially blocked-micropore layer 135 can be of any thickness, so long as it substantially blocks access of the catalytic material to the

core 120 of the catalyst particle 110. It is preferred that the catalytic layer 130 be not more than 300 micron thick, and greater than 0.5 micron thick.” *Id.*, 5:52-6:23.

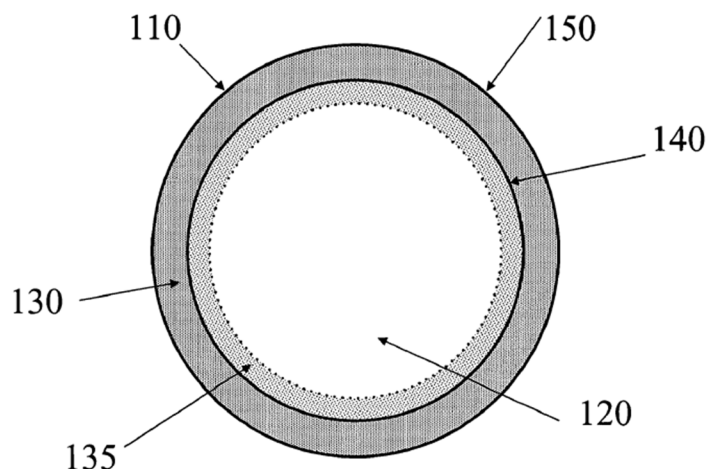


Figure 2

277. As for the support material, Espinoza states “[t]he support material may comprise any well known in the art, such as refractory support materials like *alumina*, titania, zirconia, and the like, preferably alumina. The term porous support material as used herein is meant to include all supports that have a preferred initial surface area of at least 2 m²/g and preferably at least 5 m²/g. The support structures may be monoliths, particulates or any other shape or form that can be prepared from the compositions of the present invention. Often, the shape or form selected will dictate the type of catalyst bed that must be used. For example, fixed beds are comprised of monoliths and large particle sized supports (*greater than 0.5 mm*, preferably greater than about 1 mm). Small-size support particles (*less than 0.5 mm, preferably less than 0.25 mm*) tend to be more useful

in fluidized beds. The more preferred embodiments of the present invention comprise fixed bed reactors having large to medium sized particulate type supports.” *Id.*, 7:51-67.

278. As discussed above, Espinoza is further instructive that a smaller particle size may be more appropriate in the application of fluidized catalysts whereas a larger particle size is appropriate in a fixed bed catalyst application. *Id.*, 7:51-67. Specifically, Espinoza teaches that particle size ranging from 0.5 mm to 0.25 mm are most useful in fluidized bed catalyst reactions. *Id.*, 7:51-67.

2. Analysis

(i) Claim 1

[1pre] A CO to CO₂ combustion promoter comprising microsphere sized porous particles, each microsphere sized porous particle having a diameter of less than 1mm, and independently comprising:

279. To the extent the preamble is deemed to be limiting, Espinoza-AAPA renders the preamble obvious. Espinoza discloses catalyst compositions capable of converting methane-containing gas to carbon monoxide and hydrogen (i.e., “synthesis gas” or “syngas”). Espinoza, Abstract, 1:34-53. A POSITA would recognize the similarity of chemistry in the catalytic reaction described by Espinoza to CO to CO₂ combustion reaction and that the CO to CO₂ combustion is an example of the type of reaction that would have benefited from an eggshell structure, like that disclosed by Espinoza. Espinoza additionally discloses a range of particle sizes from 0.5 mm to 0.25 mm. *Id.*, 7:51-67. Therefore, Espinoza

renders obvious a CO to CO₂ combustion catalyst including microsphere sized particles having a diameter size of less than 1mm.

280. As described above, the applicant of the '864 Patent admitted that microsphere sized particles were well known in the art. A POSITA would have been motivated to use particles ranging in size from 1 mm in diameter and smaller with the combustion promoter disclosed in Espinoza in light of the disclosure in Espinoza of particle sizes 0.5 mm to 0.25 mm.

[1a] silica, alumina, or mixtures thereof; and

281. Espinoza discloses silica, alumina, or mixtures thereof. Espinoza discloses that the catalytic composition comprises “support material such as *alumina, silica . . .*” Espinoza, 2:28-36. Espinoza further teaches that this support may comprise mixtures of silica and alumina. *Id.*, 10:22-24.

282. As described above, the applicant of the '864 Patent admitted that CO to CO₂ combustion promoters commonly comprised alumina and/or other substrate microspheres.

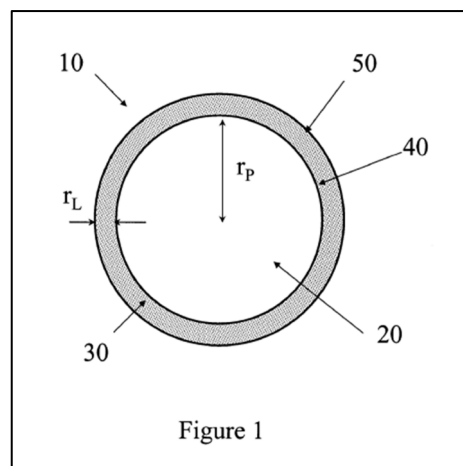
[1b] one or more Group VIII noble metals distributed in the particle as an eggshell such that a higher concentration of the one or more Group VIII noble metals is present in the outer region of the microsphere sized porous particle as compared to the concentration of the one or more Group VIII noble metals in the centre of the microsphere sized porous particle.

283. Espinoza discloses one or more Group VIII noble metals distributed in the particle as an eggshell such that a higher concentration of the one or more

Group VIII noble metals is present in the outer region of the microsphere sized porous particle as compared to the concentration of the one or more Group VIII noble metals in the center of the microsphere sized porous particle. Espinoza discloses “preferred embodiments of the present invention comprise catalyst systems comprising a core and an outer region disposed on said core, wherein a substantial amount of the catalytic metal is located in the outer region of the catalyst support matrix.” Espinoza, Abstract. Espinoza further teaches that “[t]he more preferred catalytic metals are Group VIII or noble metals, such as rhodium, platinum, or palladium” present on the outer region of the catalyst. *Id.*, 2:29-36-3:45. Further, Espinoza teaches that that not only is the content (*i.e.*, mass) of the noble metal higher in the outer region compared to the core but also the concentration (*i.e.*, mass/volume) and/or weight percentage (*i.e.*, mass/mass)⁵ of noble metal is higher in the outer region compared to the core. Espinoza, 2:50-54, 4:5-15 (“The preferred embodiments include a partial oxidation catalyst in which

⁵ A POSITA would have recognized that concentration of noble metals is often given as wt.% which is effectively mass/total mass x 100. This is often called the metal loading. It is my understanding from the Prosecution History that the Patent Office defined concentration as “mass/volume.” See ’864 Prosecution History at 212. But I also understand that Patent Owner has asserted that concentration means “mass per mass,” WRG-1016, which as I noted above would be a weight percent (mass/total mass x 100). Under either construction, it is my opinion that Espinoza discloses or renders obvious a higher concentration of the one or more Group VIII noble metals is present in the outer region of the microsphere sized porous particle as compared to the concentration of the one or more Group VIII noble metals in the centre of the microsphere sized porous particle.

wherein at least 60% of the catalytically active metal is located within 300 μm from the catalyst exterior surface. In a more preferred embodiment, the present invention comprises a catalyst having a catalytically active metal load of about 1 wt % or less, preferably of about 0.75 wt % or less, more preferably of about 0.5 wt % or less, on a support wherein at least 60% of the catalytically active metal is located within 300 μm from the catalyst exterior surface.”), 4:16-47, 5:52-6:67 (additional exemplary



or

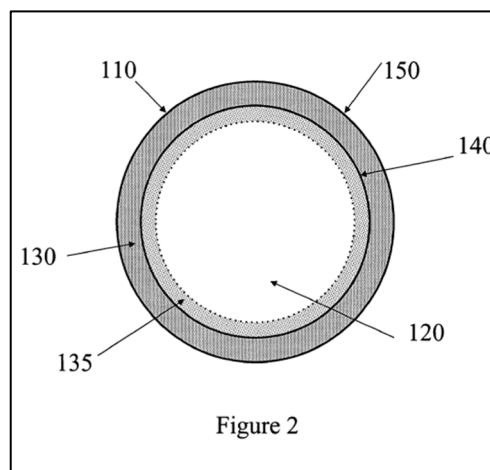
embodiments). Espinoza teaches a greater percentage of noble metal in the outer region compared to the core, “wherein at least 60% of the catalytically active metal is located within 300 μm from the catalyst exterior surface.” *Id.* For example, Espinoza teaches “[o]ne embodiment of the present invention [] for a catalyst system in which the majority of the catalytic metal is near the surface of the support matrix . . . In other words, the catalyst is not uniformly dispersed throughout the catalyst matrix, but instead has regions of differing catalyst concentration.” *Id.*, 5:52-6:23. Espinoza demonstrates this structure in Figure 1:

“[T]he support could have more than one discrete region comprising differing catalyst concentrations. As shown, the spherical catalyst system 10 has two regions 20 and 30. Region 20 is the inner core, and region 30, also called outer layer, is the area at the periphery of the core. Region 30 is delimited by exterior surface 50 of catalyst system 10 and

outer surface 40 of the region 20. In the broadest and simplest terms and in accordance with the present invention, region 20 should have a lower amount of catalyst than region 30. In other words, the catalyst material should be distributed such that if region 20 and 30 were divided into two sections of equal volume, i.e., 50-50, more than 50% of the catalytically active material would be located in region 30. In a preferred embodiment, region 20 would comprise substantially lower amounts of catalyst than region 30. The general objective being that more than 50% of the catalytically active material is located in a contiguous region of the support that comprises 50% or less of the total support volume. In a more preferred embodiment, region 20 would have substantially zero catalytic material.

Id. Espinoza depicts a similar structure in Figure 2:

In another embodiment of the present invention shown in FIG. 2, a catalyst particle 110 has a core 120 with an outer surface 140, a catalytic outer layer 130 with an exterior surface 150, and a substantially blocked-micropore layer 135. The substantially blocked-micropore layer 135 substantially prevents access to deposition of catalytic material in internal surface of core 120 of the catalyst particle 110. Thus, catalyst material are deposited primarily only on the outer surface 140 of the core 120 and form the outer layer 130. The substantially blocked-micropore layer 135 can be of any thickness, so long as it substantially blocks access of the catalytic material to the core 120 of the catalyst particle 110. It is preferred that the catalytic layer 130 be not more than 300 micron thick, and greater than 0.5 micron thick.



Id. Espinoza notes the difference from Figure 1 as “[t]he particle 10 of FIG. 1 differs from particle 110 of FIG. 2 in that the substantially blocked-micropore layer of particle 10 extends substantially throughout the core 20 of the particle 10.” *Id.*,

5:52-7:67. In this manner, as shown and described with respect to Figures 1 and 2, Espinoza teaches that the noble metals are distributed in the particle as an eggshell such that a higher concentration of the noble metals is present in the outer region as compared to the concentration of the noble metals in the center of the particle.

(ii) Claim 2

[2] The combustion promoter according to claim 1, comprising a plurality of microsphere sized porous particles comprising silica.

284. Espinoza discloses the combustion promoter comprising a plurality of microsphere sized porous particles comprising silica. Espinoza discloses that the catalytic composition comprises “support material such as alumina, *silica*” Espinoza, 2:28-36. Espinoza further teaches that this support may comprise mixtures of silica and alumina. *Id.*, 10:22-24.

(iii) Claim 3

[3] The combustion promoter according to claim 1, comprising a plurality of microsphere sized porous particles comprising alumina.

285. Espinoza discloses the combustion promoter comprising a plurality of microsphere sized porous particles comprising alumina. Espinoza discloses that the catalytic composition comprises “support material such as *alumina*, silica” Espinoza, 2:28-36. Espinoza further teaches that this support may comprise mixtures of silica and alumina. *Id.*, 10:22-24.

(iv) Claim 4

[4] The combustion promoter according to claim 1, comprising a first plurality of microsphere sized porous particles comprising silica and a second plurality of microsphere sized porous particles comprising alumina.

286. Espinoza discloses the combustion promoter comprising a first plurality of microsphere sized porous particles comprising silica and a second plurality of microsphere sized porous particles comprising alumina. Espinoza discloses that the catalytic composition comprises “support material such as *alumina, silica . . .*” Espinoza, 2:28-36. Espinoza further teaches that this support may comprise mixtures of silica and alumina. *Id.*, 10:22-24.

(v) Claim 6

[6] The combustion promoter according to claim 1, wherein the microsphere sized porous particles collectively have an average (D50) size of between 60 and 90 microns as measured by laser diffraction.

287. Espinoza-AAPA renders obvious the combustion promoter wherein the microsphere sized porous particles collectively have an average (D50) size of between 60 and 90 microns as measured by laser diffraction. As shown above, Espinoza discloses a range of particle sizes from 0.5 mm to 0.25 mm. Espinoza, 7:51-67. To the extent, Espinoza does not explicitly disclose an average size of between 60 and 90 microns, as discussed above, the applicant admitted that “*microspheres of average particle size 60 to 90 microns*” were known in the art. ’864 patent, 1:62-2:3. Further, a POSITA would have understood that laser diffraction is a common and well-known technique for measuring particle size.

Therefore, a POSITA would have known that particles having an average diameter size of less than 1mm, and an average size of between 60 and 90 microns, was known for use in CO to CO₂ combustion promoters like those disclosed in Espinoza.

(vi) Claim 12

[12] The combustion promoter according to claim 1, wherein the one or more Group VIII noble metals comprises one or more of platinum, palladium, iridium, ruthenium, and rhodium.

288. Espinoza discloses the combustion promoter wherein the one or more Group VIII noble metals comprises one or more of platinum, palladium, iridium, ruthenium, and rhodium. Espinoza discloses “preferred embodiments of the present invention comprise catalyst systems comprising a core and an outer region disposed on said core, wherein a substantial amount of the catalytic metal is located in the outer region of the catalyst support matrix.” Espinoza, Abstract. Espinoza further teaches that “[t]he more preferred catalytic metals are Group VIII or noble metals, such *as rhodium, platinum, or palladium*” present on the outer region of the catalyst. *Id.*, 2:29-36-3:45.

(vii) Claim 13

[13] The combustion promoter according to claim 12, wherein the one or more Group VIII noble metals comprises platinum and palladium.

289. Espinoza discloses the combustion promoter wherein the one or more Group VIII noble metals comprises platinum and palladium. Espinoza discloses

“preferred embodiments of the present invention comprise catalyst systems comprising a core and an outer region disposed on said core, wherein a substantial amount of the catalytic metal is located in the outer region of the catalyst support matrix.” Espinoza, Abstract. Espinoza further teaches that “[t]he more preferred catalytic metals are Group VIII or noble metals, such as rhodium, *platinum*, or *palladium*” present on the outer region of the catalyst. *Id.*, 2:29-36-3:45.

(viii) Claim 14

[14] The combustion promoter according to claim 12, wherein the one or more Group VIII noble metals comprises platinum.

290. Espinoza discloses the combustion promoter wherein the one or more Group VIII noble metals comprises platinum. Espinoza discloses “preferred embodiments of the present invention comprise catalyst systems comprising a core and an outer region disposed on said core, wherein a substantial amount of the catalytic metal is located in the outer region of the catalyst support matrix.” Espinoza, Abstract. Espinoza further teaches that “[t]he more preferred catalytic metals are Group VIII or noble metals, such as rhodium, *platinum*, or palladium” present on the outer region of the catalyst. *Id.*, 2:29-36-3:45.

(ix) Claim 15

[15] The combustion promoter according to claim 12, wherein the one or more Group VIII noble metals comprises palladium.

291. Espinoza discloses the combustion promoter wherein the one or more Group VIII noble metals comprises palladium. Espinoza discloses “preferred

embodiments of the present invention comprise catalyst systems comprising a core and an outer region disposed on said core, wherein a substantial amount of the catalytic metal is located in the outer region of the catalyst support matrix.”

Espinoza, Abstract. Espinoza further teaches that “[t]he more preferred catalytic metals are Group VIII or noble metals, such as rhodium, platinum, or *palladium*” present on the outer region of the catalyst. *Id.*, 2:29-36-3:45.

(x) Claim 18

[18pre] The combustion promoter according to claim 1, obtained by a process comprising the following steps:

292. To the extent the preamble is deemed to be limiting, Espinoza-AAPA renders obvious [18pre] for the same reasons I discussed with respect to [1pre].

293. As Espinoza recognizes, “[m]ethods for the preparation of the catalyst systems described herein are not critical. Any method by which the catalytic metal can be dispersed within the catalyst matrix in accordance with the present invention will be sufficient.” Espinoza, 8:39-59.

[18a] introducing a medium in the pores of microsphere sized porous particles having a diameter of less than 1 mm to obtain microsphere sized porous particles with filled pores; and

294. Espinoza-AAPA discloses introducing a medium in the pores of microsphere sized porous particles having a diameter of less than 1 mm to obtain microsphere sized porous particles with filled pores. As discussed above, Espinoza discloses eggshell catalyst particles having an average diameter size of less than

1mm. Espinoza, Abstract, 4:5-47, 7:51-67. For example, Espinoza discloses a method for preparing the catalytic composition to obtain the preferred eggshell structure by “applying a solution of a pore-blocking agent such as silicic acid or sodium carbonate, to the support particle.” *Id.*, 4:26-47; 8:39-59.

295. As described above, a POSITA would have combined Espinoza with the AAPA to apply the teachings of Espinoza to the full range of microsphere sized pores.

[18b] contacting the microsphere sized porous particles with filled pores with an aqueous salt solution of the one or more Group VIII noble metals,

296. Espinoza discloses contacting the microsphere sized porous particles with filled pores with an aqueous salt solution of the one or more Group VIII noble metals. Espinoza teaches a method of preparing the catalytic composition wherein “the particles are then provided a catalytically active material for catalyzing reactions, wherein the catalytically active material preferably comprises a *Group VIII metal*.” Espinoza, 4:26-47. Espinoza provides an example of loading the Group VIII metal via an aqueous salt solution of rhodium. *Id.*, 10:48-56.

[18c] wherein the one or more Group VIII noble metals deposits at a higher content in the outer region of the microsphere sized porous particles with filled pores as compared to the content of the one or more Group VIII noble metals in the centre of the microsphere sized porous particles with filled pores, thereby obtaining eggshell particles.

297. Espinoza discloses wherein the one or more Group VIII noble metals deposits at a higher content in the outer region of the microsphere sized porous

particles with filled pores as compared to the content of the one or more Group VIII noble metals in the center of the microsphere sized porous particles with filled pores, thereby obtaining eggshell particles. Espinoza teaches that the Group VIII metal is “dispersed in the outer layer, wherein the catalytically active material does not substantially penetrate and deposit into the core because of the blocked pores.” Espinoza, 4:26-47. Espinoza further teaches that the disclosed method of preparation “preferentially deposit[es] catalytic material near the outer surface of the porous catalyst support.” *Id.*, 8:39-59.

(xi) Claim 19

[19] The combustion promoter of claim 18, the process further comprising a step: (c) at least one of drying and calcining the eggshell particles.

298. Espinoza discloses at least one of drying and calcining the eggshell particles. Espinoza discloses the preparation of the eggshell catalyst composition wherein the method includes “(i) . . . **calcining** the catalyst particle such that a substantial portion of micropores of the particle are filled or blocked; (ii) immersion in water followed by **drying** at a temperature ranging from about 150°F. to about 300° F. in a microwave oven, or the like, and then **calcining** in air.” Espinoza, 8:39-59.

(xii) Claim 21

[21] The combustion promoter according to claim 18, wherein the medium in step (a) is water.

299. Espinoza discloses the medium in step (a) is water. Espinoza discloses the preparation of the eggshell catalyst composition wherein the method includes, for example, applying a solution sodium carbonate to the support particle” and “[t]he catalyst compositions were then *washed with distilled water* to remove sodium *Id.*, 4:26-47; 8:39-59, 10:40-67.

(xiii) Claim 22

[22] The combustion promoter according to claim 18, wherein in step (b) the filled microsphere sized porous particles are contacted in step (b) with a volume of the aqueous salt solution of the one or more Group VIII noble metals which is less than the total volume of the pores of the starting microsphere sized particles.

300. Espinoza discloses wherein in step (b) the filled microsphere sized porous particles are contacted in step (b) with a volume of the aqueous salt solution of the one or more Group VIII noble metals which is less than the total volume of the pores of the starting microsphere sized particles. Espinoza teaches a method of preparing the catalytic composition wherein “the particles are then provided a catalytically active material for catalyzing reactions, wherein the catalytically active material preferably comprises a Group VIII metal.” Espinoza, 4:26-47. Espinoza provides an example of loading the Group VIII metal via an aqueous salt solution of rhodium “using an appropriate quantity to achieve incipient wetness with the desired loading” of rhodium. *Id.*, 10:48-56. A POSITA would have understood that in order to incorporate a desirable level of metal compound into

the support particle on the outer region, as taught by Espinoza, the salt solution must be up to or less than the total volume of the pores of the starting microsphere sized particles. For example, a POSITA would have understood the deviating from the teaching of Espinoza and using excess solution more than the total volume of the pores would prevent the deposition of the metal compound on the outer region of the support particle.

Additional Remarks

301. I currently hold the opinions set expressed in this declaration. But my analysis may continue, and I may acquire additional information and/or attain supplemental insights that may result in added observations.

302. I declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both under Section 1001 of Title 18 of the United States Code.

Dated: June 15, 2023

By: 

EXHIBIT 1

Michael P. Harold

University of Houston

Department of Chemical & Biomolecular Engineering

S325 Engineering Building 1

Houston, TX 77204-4004

713-743-4322, mharold@uh.edu**Professional Experience**

- Cullen Engineering Professor University of Houston Houston, TX 9/20 – present
Dept. of Chemical Eng.
- ChBE Chair Professor University of Houston Houston, TX 9/19 – 8/20
Dept. of Chemical Eng.
- Department Chair University of Houston Houston, TX 2/13 – 12/20
Dept. of Chemical Eng.
- Acting Dean University of Houston Houston, TX 5/13 – 8/13
Cullen College of Eng.
- Interim Assoc. Dean of Research University of Houston Houston, TX 2/13 – 6/13
Cullen College of Eng.
- M.D. Anderson Professor University of Houston Houston, TX 12/10 – 8/19
Dept. of Chemical Eng.
- Professor University of Houston Houston, TX 9/08 – 11/10
Dept. of Chemical Eng.
- Dow Professor & Dept. Chair University of Houston Houston, TX 9/00 – 8/08
Dept. of Chemical Eng.
- Research Manager DuPont Company Wilmington, DE 6/99 – 8/00
(Chemical Process Fundamentals) DuPont Central Research
- Global Technology Manager DuPont Company Kinston, NC 12/97 – 5/99
(Polymer & Fiber R&D) DuPont Dacron®
- Research Supervisor DuPont Company Wilmington, DE 6/97 - 12/97
(Intermediates R&D) Dacron® Intermediates
- Research Associate DuPont Company Wilmington, DE 5/96 - 5/97
(Reaction Engineering R&D) Central Research and Development
- Adjunct Professor University of Delaware Newark, DE 9/94 – 8/00
Dept. of Chemical Eng.
- Adjunct Professor University of Massachusetts Amherst, MA 9/93 – 8/00
Dept. of Chemical Eng.
- Senior Research Engineer DuPont Company Wilmington, DE 7/93 - 4/96
(Reaction Engineering R&D) Central Research and Development
- Associate Professor University of Massachusetts Amherst, MA 1/91 - 6/93
(Tenured) Dept. of Chemical Eng.
- Research Fellow University of Twente Enschede, Holland 7/91 – 1/92
Dept. of Chemical Technology
- Assistant Professor University of Massachusetts Amherst, MA 3/85 - 12/90
Dept. of Chemical Eng.
- Research Assistant University of Houston Houston, TX 9/80 – 2/85
Dept. of Chemical Eng.
- Technical Service Eng. Rohm and Haas Texas Inc. Laporte, TX 6/80 – 8/80
- Production Research Eng. Gulf R&D Division Harmarville, PA 6/79 – 8/79

Education

- | | | |
|-------------------------------|------------------------------------|------|
| • Ph.D., Chemical Engineering | University of Houston | 1985 |
| • B. S., Chemical Engineering | Pennsylvania State University | 1980 |
| | Graduated with highest distinction | |

Notable Leadership Activities

- Editor-in-Chief, *AIChE Journal*; 2012 – 2022. I held this position for two full terms (maximum allowed). The *AIChE Journal* is the premier generalist research journal for the chemical engineering discipline.
- Founder and Principal Investigator of the “Texas Center for Clean Engines, Emissions & Fuels (TXCEF); 2005 – present. UH laboratory involved in the research, development, testing, and implementation of emission control technologies. involves a partnership between UH, the City of Houston, the State of Texas, and third-party companies. Since 2005 the Center has had grants awarded totaling over \$25 million.
- Chair of Catalysis and Reaction Engineering Division of AIChE; 2022, 1999. In this elected leadership role that I have held twice, the CRE Division growth accelerated, and several new initiatives were implemented. In 2022 I initiated the CRE Endowment which has collected \$50k to date.
- Industrial research and technology management experience (DuPont Company); 1997 – 2000. Involved in the research and development of proprietary reactors spanning microfabricated reactors, membrane reactors, and multi-phase reactors, and the application of reaction and process engineering tools to the improvement and optimization of existing chemical reactors and processes (1993-1997). Served in leadership role in programs to develop breakthrough technologies for manufacture of industrial polymers and their chemical intermediates, and synthetic melt-spun fibers.
- President of ISCRE Inc.; 2017-18 The International Symposium of Chemical Reaction Engineering (ISCRE) is a non-profit organization that advances CRE globally with its principal function to plan and host the biannual ISCRE conference.
- Chair of the AIChE Publications Committee; 2005-07. This role involves oversight of AIChE journals and publications, formulating strategic plan, among other duties.
- Chair of the Third North American Symposium on Chemical Reaction Engineering (NASCRE-3); 2013. This conference brought together 200 academic and industrial researchers.
- Editor of special issue in *Catal. Today* on “NO_x Reduction for Diesel and Lean Burn Engines,”; 2004.
- Committee Chair, Collaboration Success Award, Council for Chemical Research; 2007-08.

Awards and Honors

- Award for Excellence in Applied Catalysis, Southwest Catalysis Society (2019).
- Fellow, American Institute of Chemical Engineers (2014).
- Esther Farfel Award (top honor to university faculty member), University of Houston (2013).
- Excellence for Research & Scholarship, Professor Level, University of Houston (2013).
- Honorary Professor of Chemical Engineering, Tianjin University, Dept of Chemical Engin. (2013).
- Pei Yang University Lectureship, Tianjin University (2013).
- Fluor-Daniel Faculty Excellence Award, Cullen College of Engineering (2010).
- Honda Initiation Grant Award, Honda Research Institute, “*Enhancing Liquid Fuel Yield During Algae Pyrolysis in Structured Catalytic Reactors*,” (5 awarded out of 261) (2010).
- Outstanding Teaching Award, Cullen College of Engineering (2010).
- Abraham Dukler Distinguished Faculty Award, Univ. of Houston, Engineering Alumni Assoc. (2009).

- ACS Fuel Division *Richard A. Glenn Award* for Best Paper presented at ACS 2007 National Meeting Division of Fuel Chemistry (first out of 285 papers); Paper: “*Hydrogen Generation and Purification in Pd Nanopore Hollow Fiber Membrane Reactor*,” M. P. Harold and S. H. Israni (2008).
- Senior Faculty Research Excellence Award, Cullen College of Engineering, U. of Houston (2008).
- Best Applied Paper Award – Southwest Section of AIChE, 2007: Lattner, J.R., and M.P. Harold, “*Autothermal Reforming of Methanol: Experiments and Modeling*,” Catal.Today, **120**, 78-89 (2007).
- Participant in NAE “Frontiers of Engineering Symposium,” Irvine, CA, 1999.
- Best Applied Paper Award – Southwest Section of AIChE, 1999: Khinast, J., D. Luss, J.J. Ostermaier, R.McGill, and M.P. Harold, “*Continuously Stirred Decanting Reactor - Operability and Stability Considerations*,” *AIChE J.*, **44**, 372-387 (1998).
- Research Fellow, U. Twente, Dept. of Chemical Technology, Holland, 1991-92
- Outstanding Junior Faculty Award, University of Massachusetts College of Engineering, 1990
- Stella Erhardt Graduate Student Fellowship, University of Houston, 1985
- Graduate Student Research Achievement Award (Sigma Xi), U. of Houston, 1984
- Shell Oil Research Fellowship, University of Houston, 1983-1985
- Graduated with highest distinction from Penn State Univ., 6/80
- First prize paper in national competition in area of surface chemistry. Paper entitled “*A Model for Surfactant-Polymer Interactions in Tertiary Oil Recovery*,” 6/80
- Third prize presentation at Mid-Atlantic student conclave held at Drexel University, 4/80

Professional Service

External

- Editor-in-Chief, *AIChE Journal*, 2012 – 2022
- Second Vice-Chair, Vice-Chair, Chair, Past Chair, Catalysis and Reaction Engineering Division of AIChE, 2020 – present
- Editorial Board, *Chemical Engineering Reviews*, Sept. 2010 – present
- Member, International Symposia Chemical Reaction Engineering, Board, 2010 – 2022
- Review Committee, NSF ERC, Purdue University, 2020 – present
- Consultant, Omnis LLC, W.R. Grace, Ford, Johnson Matthey Inc., DuPont; 2012 - present
- Committee of Visitors, NSF CBET Division, June 2019
- President, International Symposium of Chemical Reaction Engineering Board, 2017 – 2018
- Vice President, International Symposium of Chemical Reaction Engineering Board, 2015 – 2016
- Secretary, International Symposium of Chemical Reaction Engineering Board, 2011 – 2014
- Conference Chair, NASCRE-3, Houston, TX, March 17-20, 2013
- Consulting Editor, *Ind. & Engineering Chemistry Research*, 2009 – 2011
- Member, AIChE Chemical Engineering Technology Operating Council, 2010 - 2011
- Consulting Editor, *AIChE Journal*, 2009 – 2011
- Member, Dept. Advisory Board, Chem. Eng. Dept., Penn State University, 2007 – 2011
- Chair, Collaboration Success Stories Committee, Council for Chemical Research, 2007 - 2008
- Chair, AIChE Publications Committee, 2004-2007
- Member, AIChE Publications Committee, 2000-2008
- Director, Computer and Systems Technology Division of AIChE, 2000-02
- Chair, Vice-Chair, Catalysis and Reaction Engineering Division of AIChE, 1997-99
- Served as Session Chair at:
 - AIChE Annual Meeting
 - International Symposium of Chemical Reaction Engineering (ISCRE)
 - North American Catalysis Society Conference (NAM)

- North American Membrane Society
- Reviewer of papers and proposals for Chemical Engineering (*AIChE J.*, *Chem. Eng. Sci.*, *Chem. Eng. Comm.*, *J. Hazardous Materials*), Chemistry (*Ind. Eng. Chem. Res.*, *J. Phys. Chem.*), Membranes (*J. Membrane Sci.*), Catalysis (*Catal. Today*, *Appl. Catal.*, *J. Catal.*, *Catal. Letters*, *Topics in Catal.*, *ACS Catalysis*, *ChemCatChem*), Energy (*J. Power Sources*, *International J. of Hydrogen Energy*, *Fuel*, *Applied Energy*), *Sep. Sci. and Tech.*, *Langmuir*, among others (*Science*, *Nature*)
- Reviewer of proposals for NSF, DOE, ACS-PRF, among others
- Served on multiple NSF review panels

Internal (University of Houston)

- | | |
|---|---|
| • Chairman of Department | August 2000 – August 2008,
February 2013 – December 2020 |
| • Chair, Research & Scholarship Committee (UH Faculty Senate) | 2013/14 Academic Year |
| • Member, Research & Scholarship Committee (Committee Vice Chair) | 2012/13 Academic Year |
| • Member, Research Council | 2010/11, 11/12 Academic Years |
| • Member, College of Engineering P&T Committee | 2009/10, 10/11, 11/12 Academic Years |
| • Chair, College of Engineering Promotion & Tenure Committee | 2010/11 Academic Year |
| • Chair, ECE Chair Search Committee | Fall, 2009 – 2010 |
| • Member, Dept. Faculty Search Committee | Fall, 2009 – present |
| • Vice-Chair, Provost Search Committee | Fall, 2004 – Spring, 2005 |

Honor Societies and Professional Organizations

- Member, American Institute of Chemical Engineers, 1980 - present
- Member, American Chemical Society, 2002 - present
- Member, Society of Automotive Engineers, 2005 - present

Research Interests

- Overall: Chemical Reaction Science & Engineering
- Specific: Catalytic Science and Engineering, Multi-Functional Chemical Reactors

Research Support

Since 2001, PI or Co-PI on grants totaling about \$25 million from federal agencies (NSF, DOE, EPA), state sources (Texas Commission for Environmental Quality, TCEQ), and private industry (Engelhard/BASF, Cummins, Ford, Honda, Shell, Total, among others). Details available upon request.

Refereed Publications [Number of Citations (Google Scholar): 8400, h-index: 54]

1. Harold, M. P., and D. Luss, "An Experimental Study of Steady-State Multiplicity Features of Two Parallel Catalytic Reactions," *Chem. Eng. Sci.*, **40**, 39-52 (1985).
2. Harold, M. P., M. Sheintuch, and D. Luss, "Analysis and Modeling of Multiplicity Features: 1. Nonisothermal Experiments," *Ind. Eng. Chem. Res.*, **26**, 786-793 (1987).
3. Harold, M. P., M. Sheintuch, and D. Luss, "Analysis and Modeling of Multiplicity Features: 2. Isothermal Experiments," *Ind. Eng. Chem. Res.*, **26**, 793-804 (1987).
4. Harold, M. P., and D. Luss, "Dependence of Multiplicity Features on Catalytic Activity Profile: CO

- Oxidation on Pt/Al₂O₃," *Ind. Eng. Chem. Res.*, **26**, 1616-1621(1987).
5. Harold, M. P., and K. M. Ng, "Effectiveness Enhancement and Reactant Depletion In a Partially Wetted Catalyst," *AIChE J.*, **33**, 1448-1465 (1987).
 6. Harold, M. P., and D. Luss, "Use of Bifurcation Map for Kinetic Parameter Estimation: Ethane Oxidation on Pt/Al₂O₃," *Ind. Eng. Chem. Res.*, **26**, 2092-2098 (1987).
 7. Harold, M. P., and D. Luss, "Use of Multiplicity Features for Kinetic Modeling: CO Oxidation on Pt/Al₂O₃," *Ind. Eng. Chem. Res.*, **26**, 2099-2106 (1987).
 8. Harold, M. P., "Partially Wetted Catalyst Performance in the Consecutive-Parallel Network," *AIChE J.*, **34**, 980-995 (1988).
 9. Funk G., Harold M. P., and K.M. Ng, "Effectiveness of a Partially Wetted Catalyst for Bimolecular Reaction Kinetics," *AIChE J.*, **34**, 1361-1366 (1988).
 10. Harold, M. P., "Steady-State Behavior of the Nonisothermal Partially Wetted and Filled Catalyst," *Chem. Eng. Sci.*, **43**, 3197-3216 (1988).
 11. Harold, M.P., P. Cini, B. Patenaude, and K. Venkataraman, "The Catalytically Impregnated Ceramic Tube: An Alternative Multiphase Reactor," *AIChE Symposium Series Membrane Reactor Technology*, R. Govind, ed., **85**, 26-45 (1989).
 12. Funk G., Harold M. P., and K. M. Ng, "Adsorption Effects on Partially Wetted Catalyst Performance," *Chem. Eng. Sci.*, **44**, 2509-2526 (1989).
 13. Funk, G. A., M.P. Harold, and K. M. Ng, "A Novel Model for Reaction in Trickle-Beds With Flow Maldistribution," *Ind. Eng. Chem. Res.*, **29**, 738-748 (1989).
 14. Cini, P., and M.P. Harold, "Preparation and Characterization of Modified Tubular Ceramic Membranes for Use as Catalyst Supports," *J. Membrane Sci.*, **55**, 199-225 (1991).
 15. Harold, M.P., and M.E. Garske, "Kinetics and Multiple Rate States for CO Oxidation on Platinum: I. Model Development and Multiplicity Analysis," *J. Catalysis*, **127**, 524-552 (1991).
 16. Harold, M.P., and M.E. Garske, "Kinetics and Multiple Rate States for CO Oxidation on Platinum: II. Linking UHV and High Pressure Behavior," *J. Catalysis*, **127**, 553-575 (1991).
 17. Funk, G. A., M.P. Harold, and K. M. Ng, "An Experimental Study of Reaction in a Single Partially Wetted Catalytic Pellet," *AIChE J.*, **37**, 202-214 (1991).
 18. Jones, S., K. M. Lau, and M. Harold, "Patterned Substrate Epitaxy Surface Shapes," *J. Crystal Growth*, **108**, 73-88 (1991).
 19. Cini, P., and M.P. Harold, "Experimental Study of the Tubular Multiphase Catalyst," *AIChE J.*, **37**, 997-1008 (1991).
 20. Garske, M.E., and M.P. Harold, "Observed Kinetics of an Exothermic Reaction on a Temperature-Controlled Catalytic Wire," *Chem. Eng. Sci.*, **43**, 623-644 (1992).
 21. Sullivan, D., M.P. Harold, and W.C. Conner, "Use of Fourier Transform Infrared Emission Spectroscopy as a Surface Analysis Tool," *J. Applied Spectroscopy*, **46**, 811-818 (1992).
 22. Harold, M.P., and P. Watson, "Bimolecular Exothermic Reaction with Vaporization in the Half-Wetted Slab Catalyst," *Chem. Eng. Sci.*, **48**, 981-1004 (1993).
 23. Harold, M.P., V.T. Zaspalis, K. Keizer, and A. Burggraaf, "Intermediate Product Yield Enhancement with a Catalytic Inorganic Membrane: I. Analytical Model for Isothermal and Differential Operation," *Chem. Eng. Sci.*, **48**, 2705-2725 (1993).
 24. Watson, P. and M.P. Harold, "Dynamic Effects of Vaporization With Exothermic Reaction in a Single Catalytic Pellet," *AIChE J.*, **39**, 989-1006 (1993).
 25. McManus, R., G. Funk, M. Harold, and K. M. Ng, "Effect of Liquid Maldistribution on Conversion in a Trickle-Bed Reactor: Experimental Study," *Ind. Eng. Chem. Res.*, **32**, 570-574 (1993).
 26. Harold, M.P., and K. M. Ng, "Vaporization-Induced External Dewetting of a Catalyst During an Exothermic Multiphase Reaction," *Ind. Eng. Chem. Res.*, **32**, 2975-2986, (1993).
 27. Watson, P.C., and M.P. Harold, "Rate Enhancement and Multiplicity in a Partially Wetted and Filled Pellet An Experimental Study," *AIChE J.*, **40**, 97-111(1994).
 28. Harold, M.P., C. Lee, A.J. Burggraaf, K. Keizer, V.T. Zaspalis, and R.S.A. de Lange, "Catalysis With

- Inorganic Membranes," in MRS Bulletin, v. XIX, no.4, 34-39 (1994).
29. Harold, M.P., J.J. Ostermaier, D.W. Drew, J.J. Lerou, and D. Luss, "The Continuously-Stirred Decanting Reactor: Steady-State and Dynamic Features," *Chem. Eng. Sci.*, **51**, 1777-1786 (1996).
 30. Harold, M.P. and C. Lee, "Intermediate Product Yield Enhancement with a Catalytic Inorganic Membrane: II. Nonisothermal and Integral Operation in a Back-Mixed Reactor," *Chem. Eng. Sci.*, **52**, 1923-1939 (1997).
 31. Acharya, M., B. Raich, H. Foley, M.P. Harold, and J. Lerou, "Metal Supported Carbogenic Molecular Sieve Membranes - Synthesis and Applications," *Ind. Eng. Chem. Res.*, **36**, 2924-2930 (1997).
 32. Srinivasan, R., I-M. Hsing, P.E. Berger, S. Firebaugh, K.F. Jensen, M.A. Schmidt, M.P. Harold, J.J. Lerou, and J.F. Ryley, "Micromachined Chemical Reactors for Heterogeneous Catalytic Partial Oxidation Reactions," *AIChE J.*, **43**, 3059-3069 (1997).
 33. Papavassiliou, V., C. Lee, J. Nestlerode, and M.P. Harold, "Pneumatically Controlled Transport and Reaction in Inorganic Membranes," *Ind. Eng. Chem. Res.*, **36**, 4954-4964 (1997).
 34. Khinast, J., D. Luss, J.J. Ostermaier, R. McGill, and M.P. Harold, "Continuously Stirred Decanting Reactor - Operability and Stability Considerations," *AIChE J.*, **44**, 372-387 (1998).
 35. Sullivan, D.H., M.P. Harold, and W.C. Conner, "Catalyst Transformation During NO + NH₃ Reaction Over Vanadium Oxide Using In Situ FTIR Emission Spectroscopy," *J. Catalysis*, **178**, 108-118 (1998).
 36. Khinast, J., D. Luss, T. Leib, and M.P. Harold, "Boiling Slurry Reactor: Feasible Operation and Stability," **44**, *AIChE J.* 1868-1879 (1998).
 37. Khinast, J., D. Luss, T.M. Leib, and M.P. Harold, "The Adiabatic Boiling Slurry Reactor: Influence of Axial Dispersion," *Chem. Eng. Sci.*, **54**, 502 (1999).
 38. Khinast, J., D. Luss, T.M. Leib, and M.P. Harold, "Impact of an Undesired Reaction on a Boiling Slurry Reactor," *Chem. Eng. Sci.*, **54**, 2295 (1999).
 39. Hsing, I-M., R. Srinivasan, R., M.P. Harold, K.F. Jensen, and M.A. Schmidt, "Simulations of Micromachined Chemical Reactors for Heterogeneous Partial Oxidation Reactions," *Chem. Eng. Sci.*, **55**, 3-13 (2000).
 40. Harold, M.P., and B. Ogunnaike, "Process Engineering in the Evolving Chemical Industry," *AIChE J.*, **46**, 2123-2127 (2000).
 41. Harold, M.P., P.L. Mills, and J. Nicole "New Methodologies and Reactor Types for Catalytic Process Development," *Stud. Surf. Sci. and Catal.* **133**, 87-101, Elsevier, Amsterdam (2001).
 42. Harold, M.P., B. Nair, and G. Kolios, "Hydrogen Generation in a Pd Membrane Fuel Processor: Assessment of Methanol-Based Reaction Systems," *Chem. Eng. Sci.*, **58**, 2551-2571 (2003).
 43. Lattner, J.R., and M.P. Harold, "Comparison of Conventional and Membrane Reactor Fuel Processors for Hydrocarbon-Based PEM Fuel Cell Systems," *Inter. J. of Hydrogen Energy*, **29**, 393-417 (2004).
 44. Bhattacharya, M. M.P. Harold, and V. Balakotaiah, "Shape Normalization for Catalytic Monoliths," *Chem. Eng. Sci.*, **59**, 3737-3766 (2004).
 45. Muncrief, R., K. Kabin, and M.P. Harold, "NO_x Storage and Reduction With Propylene on Pt/BaO/Alumina," *AIChE J.*, **50**, 2526-2540 (2004).
 46. Bhattacharya, M. M.P. Harold, and V. Balakotaiah, "Mass Transfer Coefficients in Washcoated Monoliths," *AIChE J.*, **50**, 2939-2955 (2004).
 47. Kabin, K., R. Muncrief, and M.P. Harold, "NO_x Storage and Reduction in a Pt/BaO/Alumina Washcoated Monolith Catalyst," *Catal. Today*, **96**, 79-89 (2004).
 48. Lattner, J.R., and M.P. Harold, "Comparison of Methanol Based Fuel Processors for PEM Fuel Cell Systems," *Appl. Catalysis B. Environmental*, **56**, 149-169 (2005).
 49. Muncrief, R., P. Khanna, K. Kabin, and M.P. Harold, "Mechanistic and Kinetic Studies of NO_x Storage and Reduction on Pt/BaO/Al₂O₃," *Catal. Today*, **98**, 393-402 (2004).
 50. Kabin, K., R. Muncrief, M.P. Harold, and Y. Li, "Dynamics of Storage and Reaction in a Monolith Reactor: Lean NO_x Reduction," *Chem. Eng. Sci.*, **59**, 5319-5327 (2004).
 51. Bhattacharya, M., M.P. Harold, and V. Balakotaiah, "Low Dimensional Models for Stirred Tank Reactors," *Chem. Eng. Sci.*, **59**, 5587-5596 (2004).

52. Sharma, M., M.P. Harold, and V. Balakotaiah, "Analysis of Periodic Storage and Reduction in Catalytic Monoliths," *Ind. Eng. Chem. Res.*, **44**, 6264-6277 (2005).
53. Sharma, M., K. Kabin, M.P. Harold, and V. Balakotaiah, "Modeling of NO_x Storage and Reduction for Diesel Exhaust Emission Control," *SAE J.*, OFL-125 (2005).
54. Sharma, M., M.P. Harold, and V. Balakotaiah, "Analysis of Storage and Reaction Phases for LNT for Diesel Engine Exhaust Treatment," *SAE J.*, OFFL-218 (2005).
55. Kabin, K., P. Khanna, R. Muncrief, V. Medhekar, and M.P. Harold, "Monolith and TAP Reactor Studies of NO_x Storage on Pt/BaO/Al₂O₃: Elucidating the Mechanistic Pathways and Roles of Pt," *Catal. Today*, **114**, 72-85 (2006).
56. Nair, B., and M.P. Harold, "Hydrogen Generation in a Pd Membrane Fuel Processor: Productivity Effects During Methanol Steam Reforming," *Chem. Eng. Sci.*, **61**, 6616-6636 (2006).
57. Theis, J., H.W. Jen, R. McCabe, M. Sharma, V. Balakotaiah, and M.P. Harold, "Reductive Elimination as a Mechanism for Purging a Lean NO_x Trap," *SAE J.*, 2006-01-1067 (2006).
58. Su, Y., K. Kabin, M.P. Harold, and M.D. Amiridis, "Reactor and In-situ FTIR Studies of Pt Pt/BaO/Al₂O₃ and Pd/BaO/Al₂O₃ NO_x Storage and Reduction (NSR) Catalysts," *Appl. Catal. B. Environmental*, **71**, 207-215 (2006).
59. Lattner, J.R., and M.P. Harold, "Autothermal Reforming of Methanol: Experiments and Modeling," *Catal. Today*, **120**, 78-89 (2007).
60. Medhekar, V., V. Balakotaiah, and M.P. Harold, "TAP Study of NO_x Storage and Reduction on Pt/Al₂O₃ and Pt/Ba/Al₂O₃," *Catal. Today*, **121**, 226-236 (2007).
61. Nair, B., J. Choi, and M.P. Harold, "Electroless Plating and Permeation Features of Pd and Pd-Ag Hollow Fiber Composite Membranes," *J. Membrane Sci.*, **288**, 67-84 (2007).
62. Nair, B., and M.P. Harold, "Pd Encapsulated and Nanopore Hollow Fiber Membranes: Synthesis and Permeation Studies," *J. Membrane Sci.*, **290**, 182-195 (2007).
63. Sharma, M., R.D. Clayton, M.P. Harold, and V. Balakotaiah, "Multiplicity in Lean NO_x Traps," *Chem. Eng. Sci., Chem. Eng. Sci.*, **62**, 5176-5181 (2007).
64. Xu, J., R.D. Clayton, V. Balakotaiah, and M.P. Harold, "Experimental and Microkinetic Modeling of Steady-State NO Reduction by H₂ on Pt/BaO/Al₂O₃ Monolith Catalysts," *Appl. Catal. B. Environmental*, **77**, 395-408(2008).
65. Muncrief, R.L., C.W. Rooks, M.P. Harold, and M. Cruz, "Combining Biodiesel and Exhaust Gas Recirculation for Reduction in NO_x and Particulate Emissions," *Energy and Fuels*, **22**, 1285-1296 (2008).
66. Clayton, R.D., M.P. Harold, and V. Balakotaiah, "Selective Catalytic Reduction of NO by H₂ in O₂ on Pt/BaO/Al₂O₃ Monolith NO_x Storage Catalysts," *Appl. Catal. B. Environmental*, **81**, 161-181 (2008).
67. Nair, B., and M.R. Harold, "Experiments and Modeling of Transport in Composite Pd and Pd/Ag Coated Alumina Hollow Fibers," *J. Membrane Sci.*, **311**, 53-67 (2008).
68. Clayton, R.D., M.P. Harold, and V. Balakotaiah, "NO_x Storage and Reduction with H₂ on Pt/BaO/Al₂O₃ Monolith: Spatio-Temporal Resolution of Product Distribution," *Appl. Catal. B. Environmental*, **84**, 616-630 (2008).
69. Xu, J., M.P. Harold, and V. Balakotaiah, "Microkinetic Modeling of Steady-State NO/H₂/O₂ on Pt/BaO/Al₂O₃ Monolith Catalysts," *Appl. Catal. B. Environmental*, **89**, 73-86 (2009).
70. Israni, S.H., B. Nair and M. P. Harold, "Hydrogen Generation and Purification in a Composite Pd Hollow Fiber Membrane Reactor: Experiments and Modeling," *Catal. Today*, **130**, 299-311 (2009).
71. Clayton, R.D., M.P. Harold, and V. Balakotaiah, "Performance Features of Pt/BaO Lean NO_x Trap with Hydrogen as Reductant," *AIChE J.*, **55**, 687-700 (2009).
72. Joshi, S., V. Balakotaiah, and M.P. Harold "Low Dimensional Models for Real Time Simulation of Catalytic Monoliths," *AIChE J.*, **55**, 1771-1783 (2009).
73. Bhatia, D., V. Balakotaiah and M.P. Harold, "Bifurcation Analysis of CO and H₂ Oxidation on Pt/Al₂O₃ Monolith Reactors," *Chem. Eng. Sci.* **64**, 1544-1558 (2009).
74. Kumar, A., V. Medhekar, M.P. Harold, and V. Balakotaiah, "NO Decomposition and Reduction on

- Pt/Al₂O₃ Powder and Monolith Catalysts Using the TAP Reactor,” *Appl. Catal. B. Environmental*, **90**, 642-651 (2009).
75. Clayton, R.D., M.P. Harold, V. Balakotaiah, and C.Z. Wan “Effect of Pt Dispersion on NO_x Storage and Reduction in Pt/BaO/Al₂O₃ Catalyst,” *Appl. Catal. B. Environmental*, **90**, 662-676 (2009).
 76. Bhatia, D., V. Balakotaiah, M.P. Harold, and R. McCabe, “Experimental and Kinetic Study of NO Oxidation on Model Pt Catalysts,” *J. Catalysis*, **266**, 106-119 (2009).
 77. Bhatia, D., R.D. Clayton, M.P. Harold, and V. Balakotaiah, “A Global Kinetic Model for NO_x Storage and Reduction on Pt/BaO/Al₂O₃ Monolithic Catalysts,” *Catal. Today*, **147S**, S250-S256 (2009).
 78. Joshi, S., M.P. Harold, and V. Balakotaiah, “On the Use of External and Internal Mass Transfer Coefficients in the Transient Modeling of Catalytic Monolith Reactors,” *Chem. Eng. Sci.*, **64**, 4976 - 4991 (2009).
 79. An, H., R. Muncrief, M.P. Harold, and H. Ismail, “Fast Screening of Alternative Diesel Fuels and Additives for NO_x Reduction,” *SAE Journal*, **2010-01-1293** (2010).
 80. Joshi, S., M.P. Harold, and V. Balakotaiah, “Overall Mass Transfer Coefficients and Controlling Regimes in Catalytic Monoliths,” *Chem. Eng. Sci.*, **65**, 1729-1747 (2010).
 81. Kumar, A., M.P. Harold, and V. Balakotaiah, “Isotopic TAP Studies of NO Decomposition and Reduction on Pt/BaO/Al₂O₃ Catalysts,” *J. Catalysis*, **270**, 214–223 (2010).
 82. Bhatia, D., R.D. Clayton, V. Balakotaiah, and M.P. Harold, “Modeling the Effect of Pt Dispersion and Temperature During Anaerobic Regeneration of a Lean NO_x Trap Catalyst,” *Catal. Today* **151**, 314–329 (2010).
 83. Israni, S., and M.P. Harold, “Methanol Steam Reforming in Pd-based Membrane Reactors: Effects of Reaction System Species on Hydrogen Flux Through a Pd-Ag membrane,” *I&EC Research*, **49**, 10242-10250 (2010).
 84. Kumar, A., M.P. Harold, and V. Balakotaiah, “Estimation of Stored NO_x Diffusion Coefficient in NO_x Storage and Reduction,” *I&EC Research*, **49**, 10334-10340 (2010).
 85. Kumar, A., X. Zheng, M.P. Harold, and V. Balakotaiah, “Microkinetic Modeling of the NO + H₂ System on Pt/Al₂O₃ Catalyst Using Temporal Analysis of Products” *J. Catalysis*, **279**, 12–26 (2011).
 86. Israni, S. and M.P. Harold, “Methanol Reforming in a Pd/Ag Membrane Reactor: Experiments and Modeling,” *J. Membrane Science*, **369**, 375-387 (2011).
 87. Joshi, S., Y. Ren, M.P. Harold, and V. Balakotaiah, “Determination of Kinetics and Controlling Regimes for H₂ Oxidation on Pt/Al₂O₃ Monolithic Catalyst Using High Space Velocity Experiments,” *Applied Catalysis B: Environmental*, **102**, 484–495 (2011).
 88. Liu, Y., M.P. Harold, and D. Luss, “Spatiotemporal Features of Pt/CeO₂/Al₂O₃ Catalysts During Lean/Rich Cycling,” *Applied Catalysis A, General*, **397**, 35-45 (2011).
 89. Metkar, P., N. Salazar, R. Muncrief, V. Balakotaiah, and M.P. Harold, “Selective Catalytic Reduction of NO with NH₃ on Iron Zeolite Monolithic Catalysts: Steady-State and Transient Kinetics,” *Applied Catalysis B: Environmental*, **104**, 110–126 (2011).
 90. Xu, J., M. Harold, and V. Balakotaiah, “Modeling the Effects of Pt Loading of NO_x Storage on Pt/BaO/Al₂O₃ Catalysts,” *Applied Catalysis B: Environmental*, **104**, 305-315 (2011).
 91. Metkar, P., V. Balakotaiah, and M.P. Harold, “Experimental Study of Mass Transfer Limitations in Fe- and Cu-Zeolite Based NH₃-SCR Monolithic Catalysts,” *Chem. Eng. Sci.*, **66**, 5192–5203 (2011).
 92. Ren, Y., and M.P. Harold, “NO_x Storage and Reduction with H₂ on Pt/Rh/BaO/CeO₂: Effects of Rh and CeO₂ in the Absence and Presence of CO₂ and H₂O,” *ACS Catalysis*, **1**, 969-988 (2011).
 93. Bugosh, G., R. Muncrief, and M.P. Harold, “Comparison of Diesel Fuel Combustion Products in a Benchtop Engine System,” *Energy and Fuels*, **25**, 4704–4712 (2011).
 94. Metkar, P., V. Balakotaiah, and M.P. Harold, “Selective Catalytic Reduction of NO_x on Combined Fe- and Cu-Zeolite Monolithic Catalysts: Sequential and Dual Layer Configurations,” *Applied Catalysis B: Environmental*, **111– 112**, 67– 80 (2012).
 95. Meisami-Azad, M., J. Mohammadpour, K. Grigoriadis, and M.P. Harold, “PCA-Based Linear Parameter Varying Control of SCR Aftertreatment System,” *Intern. J. of Control*, **85**, 114-133 (2012).

96. Joshi, S., Y. Ren, M.P. Harold, and V. Balakotaiah, "Determination of Kinetics and Controlling Regimes for Propylene and Methane Oxidation on Pt/Al₂O₃ Monolithic Catalyst Using High Space Velocity Experiments," *Ind. Eng. Chem. Res.*, **51** (22), 7482–7492 (2012).
97. Campanella, A., R. Muncrief, M.P. Harold, D. Griffith, N. Whitton, and R. Weber, "Thermolysis of Microalgae and Duckweed in a CO₂-Swept Fixed-Bed Reactor: Bio-oil Yield and Compositional Effects," *J. Bioresource Technology*, **109**, 154–162 (2012).
98. Metkar, P., M.P. Harold, and V. Balakotaiah, "Experimental and Kinetic Modeling Study of NO Oxidation: Comparison between Fe and Cu-zeolite Catalysts," *Catal. Today* **184** 115–128 (2012).
99. Dasari, P., R. Muncrief, and M.P. Harold, "Elucidating NH₃ Formation During NO_x Reduction by CO on Pt-BaO/Al₂O₃ in Excess Water," *Catal. Today*, **184**, 43–53 (2012).
100. Muncrief, R.L., Cruz, M., Ng, H., Harold, M., 2012. Impact of Auxiliary Loads on Fuel Economy and Emissions in Transit Bus Applications. *SAE World Congress*, MI, USA, 26–29 April 2012, pp. 1–12.
101. Shakya, B., M.P. Harold, and V. Balakotaiah, "Crystallite-Scale Model for NO_x Storage and Reduction on Pt/BaO/Al₂O₃: Pt Dispersion Effects on NO_x Conversion and Ammonia Selectivity," *Catal. Today*, **184**, 27–42 (2012).
102. Liu, Y., M.P. Harold, and D. Luss, "Coupled NO_x Storage and Reduction and Selective Catalytic Reduction Using Dual-layer Monolithic Catalysts," *Appl. Catal. B. Environmental*, **121–122**, 239–251 (2012).
103. Zheng, X., A. Kumar, and M.P. Harold, "Isotopic Study of Pt-Catalyzed NO Reduction by NH₃ on Pt Catalysts Using Temporal Analysis of Products," *Catal. Today*, **197**, 66–75 (2012).
104. Campanella, A., and M.P. Harold, "Pyrolysis of Microalgae and Duckweed in a Falling Solids Reactor: Effects of Process Variables and Zeolite Catalysts," *J. Biomass and Bioenergy*, **46**, 218–232 (2012).
105. Metkar, P.S., M.P. Harold, and V. Balakotaiah, "Kinetic Model of NH₃-Based Selective Catalytic Reduction of NO_x on Fe-ZSM-5 and Cu-Chabazite, and Dual Layer Fe/Cu Zeolitic Monolithic Catalysts," *Chem. Eng. Sci.*, **87**, 51–66 (2013).
106. Liu, Y., Y. Zheng, M.P. Harold, and D. Luss, "Lean NO_x Reduction on LNT-SCR Dual-layer Catalysts by H₂ and CO," *Appl. Catalysis B. Environmental*, **132–133**, 293–303 (2013).
107. Liu, Y., M.P. Harold, and D. Luss, "Lean NO_x Reduction with H₂ and CO in Dual-layer LNT-SCR Monolithic Catalysts: Impact of Ceria Loading," *Topics Catalysis*, **56**, 104–108 (2013).
108. Shrestha, S., M.P. Harold, K. Kamasamudram, and A. Yezerets, "Ammonia Oxidation on Structured Composite Catalysts," *Topics in Catalysis*, **56**, 182–186 (2013).
109. Dasari, P., R. Muncrief, and M.P. Harold, "Cyclic Lean Reduction of NO by CO in Excess H₂O on Pt-Rh/Ba/Al₂O₃: Elucidating Mechanistic Features and Catalyst Performance," *Topics in Catalysis*, **56**, 1922–2936 (2013).
110. Nguyen, H., M.P. Harold, and D. Luss, "Optical Frequency Domain Reflectometry Measurements of Spatio-temporal Temperature Inside Catalytic Reactors: Applied to Study Wrong-way Behavior," *Chem. Eng. J.*, **234**, 312–317 (2013).
111. Raj, R. M.P. Harold and V. Balakotaiah, "NO Inhibition Effects During Oxidation of Propylene on Cu-Chabazite Catalyst: A Kinetic and Mechanistic Study," *Ind. Eng. Chem. Res.*, **52**, 15455–15465 (2013).
112. Shakya, B., M.P. Harold, and V. Balakotaiah, "Effect of cycle time on NH₃ generation on Low Pt Dispersion Pt/BaO/Al₂O₃: Experiments and Crystallite-Scale Modeling," *Chem. Eng. Journal*, **230**, 584–594 (2013).
113. Shakya, B., M.P. Harold, and V. Balakotaiah, "Modeling and Analysis of Dual-layer NO_x Storage and Reduction and Selective Catalytic Reduction Monolithic Catalyst," *Chem. Eng. Journal*, **237**, 109–122 (2014).
114. Zheng, Y., Y. Liu, M.P. Harold, and D. Luss, "Optimization of LNT-SCR Dual-layer Catalysts for Lean NO_x Reduction for Diesel NO_x Emission Control," *Appl. Catalysis B. Environmental*, **148**, 311–321 (2014).
115. Zheng, Y., M.P. Harold, and D. Luss, "Optimization of LNT-SCR Dual-layer Catalysts for Lean NO_x Reduction by H₂ and CO," *SAE Journal*, 2014-01-1544 (2014).

116. Shrestha, S., M.P. Harold, K. Kamasamudram, and A. Yezerets, "Selective Oxidation of Ammonia on Mixed and Dual-Layer Fe-ZSM-5 + Pt/Al₂O₃ Monolithic Catalysts," *Catal. Today*, **231**, 105-115 (2014).
117. Perng, C., V. Easterling, and M.P. Harold, "Fast Lean-Rich Cycling for Enhanced NO_x Conversion on Storage and Reduction Catalysts," *Catal. Today*, **231**, 125-134 (2014).
118. Raj, R. M.P. Harold and V. Balakotaiah, "Kinetic Modeling of NO Selective Reduction with C₃H₆ over Cu-SSZ13 Monolithic Catalyst," *Chem. Eng. Journal*, **254**, 452-462 (2014).
119. Bugosh, G., V. Easterling, and M.P. Harold, "Anomalous Steady-State and Spatio-Temporal Features of Methane Oxidation on Pt/Pd/Al₂O₃ Monolith Spanning Lean and Rich Conditions," *Applied Catalysis B. Environmental*, **165**, 68-78 (2015).
120. Nguyen, H., M.P. Harold, and D. Luss, "Spatiotemporal Behavior of Pt/Rh/CeO₂/BaO Catalyst During Lean-Rich Cycling," *Chem. Eng. Journal*, **262**, 464-477 (2015).
121. Shakya, B., M.P. Harold, and V. Balakotaiah, "Simulations and Optimization of Combined Fe- and Cu-Zeolite SCR Monolith Catalysts," *Chem. Eng. Journal*, **278**, 374-384 (2015).
122. Shrestha, S., M.P. Harold, and K. Kamasamudram, "Experimental and Modeling Study of Selective Ammonia Oxidation on Multi-Functional Washcoated Monolith Catalysts," *Chem. Eng. Journal*, **278**, 24-35 (2015).
123. Zheng, Y., M. Li, M.P. Harold, and D. Luss, "Enhanced Low-temperature NO_x Conversion by High-Frequency Hydrocarbon Pulsing on a Dual Layer LNT-SCR Catalyst," *SAE Journal*, **2015-01-0984** (2015).
124. Raj, R. M.P. Harold and V. Balakotaiah, "Steady-state and Dynamic Hysteresis Effects During Lean Co-oxidation of CO and C₃H₆ over Pt/Al₂O₃ Monolithic Catalyst," *Chem. Eng. J.*, **281**, 322-333 (2015).
125. Zheng Y., M.P. Harold, and D. Luss, "Rapid Propylene Pulsing for Enhanced Low Temperature NO_x Conversion on Combined LNT-SCR Catalysts," *Catal. Today*, **267**, 192-201 (2016).
126. Zheng Y., M.P. Harold, and D. Luss, "Effects of CO, H₂, and C₃H₆ on Cu-SSZ-13 Catalyzed NH₃-SCR," *Catal. Today*, **264**, 44-54 (2016).
127. Li, M., V. Easterling, and M.P. Harold, "Towards Optimal Operation of Sequential NO_x Storage and Reduction and Selective Catalytic Reduction," *Applied Catalysis B. Environmental*, **184**, 364-380 (2016).
128. Shrestha, S., M.P. Harold, K. Kamasamudram, A. Kumar, L. Olsson, and K. Leistner, "Selective Oxidation of Ammonia to Nitrogen on Bi-Functional Cu-SSZ-13 and Pt/Al₂O₃ Monolith Catalyst," *Catal. Today*, **267**, 130-144 (2016).
129. Li, M., V. Easterling, and M.P. Harold, "Spatio-temporal Features of Lean NO_x Reduction the Sequential NO_x Storage and Reduction and Selective Catalytic Reduction Reactor System," *Catal. Today*, **267**, 177-191 (2016).
130. Nguyen, H., M.P. Harold, and D. Luss, "Assessing Intrusion by the Capillary During Spatially Resolved Mass Spectrometry Measurement," *Chem. Eng. Journal*, **307**, 845-859 (2017).
131. Bugosh, G., and M.P. Harold, "Impact of Zeolite Beta on Hydrocarbon Trapping and Light-off Behavior of Pt/Pd/Al₂O₃ Monolith Catalysts," *Emission Control Science and Technology*, **3**, 123-134 (2017).
132. Ting, W.-L., M. Li, M.P. Harold, and V. Balakotaiah, "Fast Cycling in a Non-isothermal Monolithic Lean NO_x Trap Using H₂ as Reductant: Experiments and Modeling," *Chem. Eng. J.*, **326**, 419-435 (2017).
133. Lang, W., P. Laing, Y. Cheng, C. Hubbard, and M.P. Harold, "Co-Oxidation of CO and Propylene on Pd/CeO₂-ZrO₂/Al₂O₃ Monolith Catalysts: A Light-off, Kinetics, and Mechanistic Study," *Appl. Catal. B. Environ.*, **218**, 430-442 (2017).
134. Li, M., Y. Zheng, D. Luss, and M.P. Harold, "Impact of Rapid Cycling Strategy on Reductant Effectiveness During NO_x Storage and Reduction," *Emission Control Science and Technology*, **3**, 205-219 (2017).
135. Peng, P.-Y., H. Nguyen, M.P. Harold, and D. Luss, "Spatio-Temporal Phenomena in Monolithic

- Reactors Measured by Combined Spatially-Resolved Mass Spectrometry and Optical Frequency Domain Reflectometry,” in *Advances in Chemical Engineering*, **50**, 83-130 (2017).
136. Aseem, M.T. Conato, G. Goodwin, J. D. Rimer and M. P. Harold, “Oxidative Coupling of Methane over Mixed Metal Oxide Catalysts: Steady State Multiplicity and Catalyst Durability,” *Chem. Eng. Journal*, **331**, 132-143 (2018).
 137. Aseem and M. P. Harold, “C₂ Yield Enhancement During Oxidative Coupling of Methane in a Nonpermselective Porous Membrane Reactor,” *Chem. Eng. Science*, **175**, 199-207 (2018).
 138. Peng, P.-Y., H. Nguyen, M.P. Harold, and D. Luss, “Sustained Concentration and Temperature Oscillations in a Diesel Oxidation Catalyst,” *Chem. Eng. Journal*, **336**, 531-543 (2018).
 139. Tanwar, M., D. Bhatia, and M.P. Harold, “Analysis of Inter-particle Dilution Effects in a Catalytic Packed Bed Reactor,” *Chem. Eng. Journal*, **337**, Pages 750-754 (2018).
 140. Ting, W.-L., M. Li, M.P. Harold, and V. Balakotaiah, “Elucidating the Mechanism of Fast Cycling NO_x Storage and Reduction Using C₃H₆ and H₂ as Reductants,” *Chem. Eng. Sci.*, **189**, 413-421 (2018).
 141. Ting, W.-L., M. Li, M.P. Harold, and V. Balakotaiah, “Fast Cycling NO_x Storage and Reduction: Identification of an Adsorbed Intermediate Pathway,” *Catalysis Letters*, **148**, 1951–1964 (2018).
 142. Malamis, S., M. Li, W.S. Epling, and M.P. Harold, “Steady State and Lean-Rich Cycling Characterization of a Three-Way NO_x Storage Catalyst: Experiments,” *Appl. Catal. B. Environmental*, **237**, 588-602 (2018).
 143. Zhou, Z., M.P. Harold, and D. Luss, “NO_x Reduction on Ceria: Impact of Lean-Rich Cycling,” *Appl. Catal. B. Environmental*, **240**, 79-91 (2018).
 144. Peng, P.-Y., M.P. Harold, and D. Luss, “Coupled Hydrocarbon Desorption in Zeolite Beta,” *Ind. Eng. Chem. Res.*, **57**, 17516–17521 (2018).
 145. Peng, P.-Y., M.P. Harold, and D. Luss, “Sustained Concentration and Temperature Oscillations in a Diesel Oxidation Catalyst: Predictive Model,” *Chem. Eng. Journal*, **355**, 661-670 (2019).
 146. Dhillon, P.S., M.P. Harold, A. Kumar, D. Wang, and S. Joshi, “Enhanced Transport in Washcoated Monoliths: Application to Selective Lean NO_x Reduction and Ammonia Oxidation,” *Chem. Eng. Journal*, **377**, 119734 (2019).
 147. Dhillon, P.S., M.P. Harold, A. Kumar, D. Wang, and S. Joshi, “Hydrothermal Aging of Pt/Al₂O₃ Monolith: Washcoat Morphology Degradation Effects Studied Using Ammonia and Propylene Oxidation,” *Catal. Today*, **320**, 20-29 (2019).
 148. Li, M., S. Malamis, W.S. Epling, and M.P. Harold, “Steady State and Lean-Rich Cycling Characterization of a Three-Way NO_x Storage Catalyst: Modeling,” *Appl. Catal. B. Environmental*, **242**, 469-484 (2019).
 149. Ting, W.-L., M. Li, M.P. Harold, and V. Balakotaiah, “Fast Cycling NO_x Storage and Reduction: Modeling and Analysis of Reaction Pathways, Transport and Reductant Effects,” *Chem. Eng. Journal*, **370**, 1493-1510 (2019).
 150. Lang, W. and M.P. Harold, “Rate Inhibition and Enhancement on Ceria-Promoted Pd Monolith Catalysts: Oxidation of Acetylene, Ethylene and Propylene and Their Mixtures,” *Ind. Eng. Chem. Res.*, **58**, 6350-6363 (2019).
 151. Dhillon, P.S., M.P. Harold, A. Kumar, D. Wang, and S. Joshi, “Modeling and Analysis of Transport and Reaction in Washcoated Monoliths: Cu-SSZ-13 SCR and Dual-Layer Cu-SSZ-13 + Pt/Al₂O₃ ASC,” *Reaction Chemistry and Engineering*, **4**, 1103-1115 (2019).
 152. Zhou, Z., M.P. Harold, and D. Luss, “Comparison of Pt-BaO/Al₂O₃ and Pt-CeO₂/Al₂O₃ for Fast Cycling NO_x Storage and Reduction,” *Appl. Catal. B. Environ.*, **255**, 117742 (2019).
 153. Malamis, S., M. Ambast, M.P. Harold, and W.S. Epling “Coupled NO and C₃H₆ Trapping, Release and Conversion on Pd-BEA,” *Ind. Eng. Chem. Res.*, **58**, 22912-22923 (2019).
 154. Ghosh, R., T. Le, T. Terlier, J.D. Rimer, M.P. Harold, and D. Wang “Enhanced Selective Oxidation of Ammonia in a Pt/Al₂O₃@Cu/ZSM-5 Core–Shell Catalyst,” *ACS Catalysis*, **10**, 6, 3604-3617 (2020).
 155. Ambast, M., K. Karinshak, B. M. Rahman L. Grabow, and M.P. Harold, “Passive NO_x Adsorption on Pd/H-ZSM-5: Experiments and Modeling,” *Appl. Catal. B. Environ.*, **269**, 118802 (2020).

156. Karinshak, K. A., P. Lott, O. Deutschmann, and M.P. Harold, "In Situ Activation of Bimetallic Pd-Pt Methane Oxidation Catalysts," *ChemCatChem*, **12**, 3712–3720 (2020).
157. Gupta, A., S. Kang, and M.P. Harold, "NO_x Uptake and Release on Pd/SSZ-13: Impact of Feed Composition and Temperature," *Catal. Today*, **360**, 411-425 (2021).
158. Zhou, Z., M.P. Harold and D. Luss, "Enhanced NO, CO and C₃H₆ Conversion on Pt/Pd Catalysts: Impact of Oxygen Storage Material and Catalyst Architecture," *Catal. Today*, **360**, 375-387 (2021).
159. Dhillon, P.S., M.P. Harold, A. Kumar, D. Wang, and S. Joshi, "Optimizing the Dual-Layer Pt/Al₂O₃ + Cu/SSZ-13 Washcoated Monolith: Selective Oxidation of NH₃ to N₂," *Catal. Today*, **360**, 426-434 (2021).
160. Malamis, S. and M.P. Harold, "Optimizing the Lean Hydrocarbon NO_x Trap: Sequential and Dual-Layer Configurations," *Catal. Today*, **360**, 388-400 (2021).
161. Kang, S.B. K. Karinshak, P.W. Chen, S. Golden, and M. P. Harold, "Coupled Methane and NO_x Conversion on Pt+Pd/Al₂O₃ Monolith: Conversion Enhancement Through Feed Modulation and Mn_{0.5}Fe_{2.5}O₄/Al₂O₃ Spinel Addition," *Catal. Today*, **360**, 284-293 (2021).
162. Ghosh, R., P.S. Dhillon, M.P. Harold, and D. Wang "Kinetics of NH₃ Oxidation on Pt/Al₂O₃: Rate Enhancement and NH₃ Inhibition," *Chem. Eng. J.*, **417**, 128273 (2021).
163. Ambast, M., A. Gupta, B. M. Rahman L. Grabow, and M.P. Harold, "NO_x Adsorption with CO and C₂H₄ on Pd/SSZ-13: Experiments and Modeling," *Appl. Catal. B. Environ.*, **286**, 119871 (2021).
164. Zhou, Z., M.P. Harold and D. Luss, "Dynamic Oxygen Storage Capacity of Ceria-Zirconia and Mn_{0.5}Fe_{2.5}O₄ Spinel: Experiments and Modeling," *Ind. Eng. Chem. Res.*, **60**, 18, 6465–6482 (2021).
165. Ghosh, R., M.P. Harold, and D. Wang "Selective Oxidation of NH₃ in a Pt/Al₂O₃@Cu/ZSM-5 Core-Shell Catalyst: Modeling and Optimization," *Chem. Eng. J.*, **418**, 129065 (2021).
166. Ambast, M., A. and M.P. Harold, "Coupled Uptake and Conversion of C₁₂H₂₆ and NO on Pd/SSZ-13: Experiments and Modeling," *Chem. Eng. J.*, **423**, 129958 (2021).
167. Karinshak, K., P.W. Chen, R.F. Liu, and M. P. Harold, "Optimizing Feed Modulation for Coupled Methane and NO_x Conversion over Pd-Pt/Mn_{0.5}Fe_{2.5}O₄/Al₂O₃ Monolith Catalyst," *Appl. Catal. B. Environ.*, **304**, 120607 (2022).
168. Chen, P.W., D. Maiti, L. Grabow, and M.P. Harold, "CH₄ Steam Reforming on Pt+Pd/Al₂O₃ Monolith: Impact of Mn_{0.5}Fe_{2.5}O₄ Spinel Addition", *Catalysis Science and Technology*, **12**, 2618-2633 (2022).
169. Gupta A., M. Ambast and M.P. Harold, "NO_x and Hydrocarbon Trapping and Conversion in a Sequential Three-Zone Monolith: Spatiotemporal Features," *ACS Eng. Au*, **8**, 515-534 (2022).
170. Song, G., W. Zhou, C. Li, F. Hu, T. Wang, Z. Li, A. Tang, M.P. Harold, and S. Kawi, "Semi-hollow LTA zeolite membrane for water permeation in CO₂ hydrogenation to methanol," *J. Membrane Sci.*, **678**, 121666 (2023).

In Review:

171. Fang, C. and M.P. Harold, "Sulfur Poisoning and NH₃ Regeneration of Pt/Al₂O₃ Monolith Catalyst," *ACS Catalysis*, in review, June 2023.
172. Ratcliff, J., K. Karinshak, P.W. Chen, and M.P. Harold, "Rich Methane Oxidation on Pt+Pd/Al₂O₃: Steady State Performance, Multiplicity Features, and Spatial Patterns", *Chem. Eng. Sci.*, in review, June 2023.
173. Solanki, S.P.S., M. Ambast, A. Gupta, C. Paolucci, M.P. Harold, and L. Grabow, "Complete Mechanism for NO_x Adsorption and Release on Atomically Dispersed Palladium in Pd-CHA," *ACS Catalysis*, in review, June 2023.

To be Submitted:

174. Morales, A., P. Bollini, and M.P. Harold, "Dynamic Rate Analysis for Low Frequency Operation of Chemical Reactors," *Chem. Eng. Sci.*, to be submitted, July 2023.
175. Chen, P.W., D. Maiti, R.F. Liu, L. Grabow, and M.P. Harold, "Enhanced CH₄ oxidation over PGM/Spinel oxide catalysts via dynamic operation," *ACS Catalysis*, to be submitted, July 2023.

176. Chen, P.W., D. Maiti, L. Grabow, and M.P. Harold, "Enhanced CH₄ Oxidation Conversion Over PGM/Spinel Oxide Dual Layer Catalysts," *Chem. Eng. J.*, to be submitted, July 2023.
177. Chen, P.W., R.F. Liu, L. Grabow, and M.P. Harold, "Water Gas Shift and Methane Steam Reforming Kinetics for a Pt+Pd/Al₂O₃ Monolith Catalyst," *Ind. Eng. Chem. Res.*, to be submitted, July 2023.

Invited Reviews and Book Chapters:

178. Nagarajan R., and M. P. Harold, "Surfactant-Polymer Interactions in Tertiary Oil Recovery," in Solution Behavior of Surfactants, K. L. Mittal, ed., Plenum Press, New York, 1391-1413 (1982).
179. Harold, M.P., "Impact of Wetting on Catalyst Performance in Multiphase Catalytic Reaction Systems," Computer Aided Design of Catalysts, R. Becker and C. Pereira, eds., Marcel Dekker, 391-470 (1993).
180. Keizer, K., V.T. Zaspalis, R. de Lange, M.P. Harold, and A.J. Burggraaf, "Membrane Reactors for Dehydrogenation and Partial Oxidation," in Membrane Processes in Separation and Purification, Kluwer Academic, Dordrecht (1994).
181. Mills, P.L., M.P. Harold, and J.J. Lerou, "Industrial Heterogeneous Gas-Phase Oxidation Processes," Catalysis Monograph, van Santen, R., ed., NIOK, Amsterdam (1995).
182. Lerou, J.J., M.P. Harold, J. Ryley, J. Ashmead, T.C. O'Brien, M. Johnson, J. Perrotto, C.T. Blaisdell, T.A. Rensi, and J. Nyquist, "Microfabricated Minichemical Systems: Technical Feasibility," in Microsystem Technology for Chemical and Biological Microreactors, DECHEMA Monographs Vol.132, Workshop on Microsystem Technology, Mainz, Germany, 51-69 (1995).
183. Sirkar, K., P. Puri, A. Y. Tonkovich, R. Baker, D. Bhattacharyya, D. E. Fain, M. Harold, J. Hestekin, J. Lin, and H. Wijmans, "Membrane Technologies," in Emerging Separation and Separative Reaction Technologies for Process Waste Reduction. Adsorption and Membrane Systems, P.P. Radecki, J.C. Crittenden, D.R. Shonnard, and J.L. Bulloch, eds., Center for Waste Reduction Technologies, AIChE, New York (1999).
184. Harold, M.P., and V. Balakotaiah, "Catalytic Aftertreatment of NO_x from Diesel Exhaust," McGraw-Hill Yearbook of Science and Technology 2010, McGraw-Hill, New York, 59-62 (2010).
185. Harold M.P., and R. Krishnamoorti, "Chemical Engineering at the University of Houston," *Chemical Engineering Education*, **45**, 150-154 (2011).
186. Harold, M.P., "NO_x Storage and Reduction in Lean Burn Vehicle Emission Control: A Catalytic Engineer's Playground," *Current Opinion in Chemical Engineering*, **1**, 303-311 (2012).
187. Harold, M.P., and P. Metkar, "Selective Catalytic Reduction on Fe-Exchanged Zeolites," in Urea-SCR Technology for deNO_x After Treatment of Diesel Exhausts, I. Nova and E. Tronconi, (Eds.), Springer, New York, pp. 311-356 (2014).
188. Chen, Y., Y. Wu, D.Hua, C. Li, M.P. Harold, J. Wang, and M.Yang, "Catalytic Thermochemical Conversion for the Production of Liquid Fuels from Low-lipid Microalgae: Challenges and Opportunities," *RSC Chemistry*, **5**, 18673-18701 (2015).
189. Morgan, K., N. Maguire, R. Fushimi, J. T. Gleaves, A. Goguet, M.P. Harold, E.V. Kondratenko, Y. Schuurman, and G. S. Yablonsky, "Forty Years of Temporal Analysis of Products," *Catalysis Science and Technology*, **7**, 2416-2439 (2017).
190. Ting, W.-L., V. Balakotaiah, and M.P. Harold, "NO_x Storage and Reduction: Effects of Pt Dispersion, Reductant Type, and Cycle Timing," in NO_x Trap Catalysts and Technologies: Fundamentals and Industrial Applications, L. Lietti and L. Castoldi, (Eds.) Royal Society of Chemistry (2018).
191. Abraham, M. A., M.P. Harold, M. Ricci, "Get Your Research Published" *Chemical Engineering Progress*, **115** (11), 42-48 (2019).
192. Mallapragada, D.S., Y. Dvorkin, M. Modestino, D. V. Esposito, W. Smith, B.-M. Hodge, M. P. Harold, V. M. Donnelly, A. Nuz, C. Bloomquist, K. Baker, L. C. Grabow, Y. Yan, N. Nidhi Rajput, R. Hartman, E. Biddinger, E. Aydil, A. Taylor, "Decarbonization of the Chemical Industry through Electrification: Barriers and Opportunities," *Joule*, **7**, 23-41 (2023).

Others:

- Harold, M.P., "BOOK REVIEW: Rate Equations of Solid-Catalyzed Reactions," *J. Catalysis*, **141**, 740

(1993).

- Harold, M.P., "BOOK REVIEW: Structured Catalysts and Reactors," *Applied Catalysis A* (1999).
- Harold, M.P., "A Challenge for Our Discipline and Some New Editorial Initiatives," *AIChE Journal*, **58**, 2-3 (Jan 2012).
- Harold, M.P., "A Progress Report," *AIChE Journal* **59** (Jan 2013).
- Harold, M.P., "The Importance of Original Work," *AIChE Journal*, **60** (April 2013).
- Harold, M.P., and G. Stephanopoulos, "Tribute to Founders: Neal R. Amundson," *AIChE Journal*, **60** (September 2013).
- Harold, M.P., I. Grossmann, and M. Mavrikakis, "Tribute to Founders: R. Byron Bird," *AIChE Journal*, **61** (April 2014).
- O'Connell, J., P. Cummings, and M.P. Harold, "Tribute to Founders: John M. Prausnitz," *AIChE Journal*, **62** (September 2015).
- Harold, M.P., "A Progress Report," *AIChE Journal*, **63** (February 2016).
- Grossmann, I., and M.P. Harold, "Tribute to Founders: Roger Sargent," *AIChE Journal*, **64** (September 2016).
- S. Sundaresan, J. Curtis, C. Hrenya, and M.P. Harold, "Tribute to Founders: Roy Jackson," *AIChE Journal*, **65** (December 2017).
- M.P. Harold, "Editorial: The Inaugural Futures Issue," *AIChE Journal* <https://doi.org/10.1002/aic.16331> (August 2018).
- W. Chen, D. Clark, C. Khosla, and M.P. Harold, "Tribute to Founders: Jay Bailey," *AIChE Journal*, **66** (December 2018).
- W. Chen, C. Collins, P. Cirino, and M.P. Harold and M.P. Harold, "Tribute to Founders: Frances Arnold," *AIChE Journal*, **68** (January 2020).
- M.P. Harold, "Editorial: The Second Futures Issue," *AIChE Journal*, <https://doi.org/10.1002/aic.16839> (December 2019).
- M.P. Harold, "Editorial: The Third Futures Issue," *AIChE Journal*, <https://aiche.onlinelibrary.wiley.com/doi/10.1002/aic.17108> (December, 2020).
- M.P. Harold, "Editorial: The Fourth Futures Issue," *AIChE Journal*, <https://aiche.onlinelibrary.wiley.com/doi/10.1002/aic.17502> (December, 2021).
- M.P. Harold, "Editorial," *AIChE Journal*, <https://aiche.onlinelibrary.wiley.com/doi/10.1002/aic.17513> (December, 2021).

Invited Talks

1. Chemical Engineering Department of University of Massachusetts, *Steady-State Multiplicity in Catalytic Reactions*, 2/84.
2. Chemical Engineering Department of University of Illinois, *Steady-State Multiplicity in Catalytic Reactions*, 2/84.
3. Chemical Engineering Department of California Institute of Technology, *Steady-State Multiplicity in Catalytic Reactions*, 2/84.
4. Chemical Engineering Department of Stanford University, *Steady-State Multiplicity in Catalytic Reactions*, 2/84.
5. Chemical Engineering Department of Cornell, *Steady-State Multiplicity in Catalytic Reactions*, 3/84.
6. Chemical Engineering Department of University of Virginia, *Steady-State Multiplicity in Catalytic Reactions*, 3/84.
7. Chemical Engineering Department of University of Delaware, *Steady-State Multiplicity in Catalytic Reactions*, 3/84.
8. Chemical Engineering Department of Tufts University, *Catalyst Performance in Multiphase Reactions: The Role of Wetting*, 4/89.
9. Chemical Engineering Department of Yale University, *Catalyst Performance in Multiphase*

- Reactions: The Role of Wetting*, 4/89.
10. Chemical Engineering Department of University of Cincinnati, *Catalyst Performance in Multiphase Reactions: The Role of Wetting*, 4/89.
 11. Chemical Engineering Department of University of Massachusetts, *The Impact of Wetting in Multiphase Reactions: Modeling and Experiment*, 9/89.
 12. Chemical Engineering Department of Pennsylvania State University, *Multiple Steady-State Rates in CO Oxidation on Platinum: Kinetic Model Development and Discrimination*, 2/90.
 13. Mathematics Department of University of Massachusetts, *Steady-State Multiplicity in Surface Catalyzed Reactions*, 3/90.
 14. Catalysis Research Department at the Experimental Station, DuPont, *Multiple Steady-State Rates in CO Oxidation on Platinum: Kinetic Model Development and Discrimination*, 5/90.
 15. Catalysis Group at Yale University, *Multiple Steady-State Rates in CO Oxidation on Platinum: Kinetic Model Development and Discrimination*, 7/90.
 16. Chemical Engineering Department of the University of Pennsylvania, *The Role of Wetting in Multiphase Catalytic Reactions: Rate Enhancement by Partial Wetting*, 9/90.
 17. Institute of Organic Technology, Prague, Czechoslovakia, *Impact of Wetting on Catalyst Performance in Multiphase Reaction Systems*, 11/91.
 18. Department of Chemical Technology, University of Twente, *Applications of Inorganic Membranes in Multiphase and Partial Oxidation Reaction Systems*, 12/91.
 19. Rijksuniversiteit Gent, Gent, Belgium, *Impact of Wetting on Catalyst Performance in Multiphase Reaction Systems*, 1/92.
 20. Catalysis Research Department at the Experimental Station, DuPont Company, *Hydrogenation and Partial Oxidation with Inorganic Catalytic Membranes*, 2/92.
 21. The Membrane Conference on Technology/Planning, Boston, MA, *Hydrogenation and Partial Oxidation with Inorganic Catalytic Membranes*, 9/92.
 22. North American Catalysis Society National Meeting, Pittsburgh, PA, *Improving Desired Product Yield with Catalytic Inorganic Membranes*, 5/93.
 23. Shell Research and Development, Houston, TX, *Overall Rate and Selectivity Improvements with Catalytic Inorganic Membranes*, 5/93.
 24. Gordon Research Conference on Membranes, Plymouth State College, Plymouth, NH, *Overall Rate and Selectivity Improvements with Catalytic Inorganic Membranes*, 8/93.
 25. Department of Chemical Engineering, State University of New York at Buffalo, *Improved Reactor Contacting Strategies Using Inorganic Membrane Reactors: Yield Improvement in Consecutive-Parallel Reaction Systems*, 11/95.
 26. Department of Industrial Catalysis, *Industrial Heterogeneous Gas Phase Oxidation Processes*, Delft University of Technology, 8/96.
 27. Department of Chemical and Petroleum Engineering, University of Pittsburgh, *Oxygenate Yield Improvement in Selective Oxidation Reactions with Inorganic Membrane Reactors*, 10/96.
 28. Department of Chemical Engineering, Notre Dame University, *New Reactor Types for Safe and Selective Oxidation of Hydrocarbons*, 3/97.
 29. UOP Research Center, Des Plaines, Illinois, *New Reactor Types for Safe and Selective Oxidation of Hydrocarbons*, 10/97.
 30. Washington D.C. - Capital District Section of AIChE, Arlington, VA, *New Reactor Types for Safe and Selective Oxidation of Hydrocarbons*, 11/97.
 31. DuPont Company Central Research & Development, several research reviews presented to senior management, 1994-99.
 32. Department of Chemical Engineering, Rutgers University, *New Reactor Types for Safe and Selective Oxidation of Hydrocarbons*, 2/99.
 33. Department of Chemical Engineering, University of Michigan, *New Reactor Types for Safe and Selective Oxidation of Hydrocarbons*, 11/99.

34. Department of Chemical Engineering, Purdue University, *Synthesis, Analysis, and Multi-Disciplinary Teams in Chemical Engineering Research*, 11/99.
35. Department of Chemical Engineering, University of Houston, *Synthesizing New Reactor Types with Improved Safety, Selectivity, and Scalability*, 3/00.
36. Department of Chemical Engineering, University of Pennsylvania, *Synthesizing New Reactor Types with Improved Safety, Selectivity, and Scalability*, 4/00.
37. Department of Chemical Engineering, Rice University, *New Reactor Types for Safe and Selective Oxidation of Hydrocarbons*, 12/00.
38. Department of Chemical Engineering, University of Oklahoma, *New Reactor Types for Improved Safety, Selectivity, and Productivity*, 11/01.
39. Department of Chemical Engineering, Tulane University, *New Reactor Types for Improved Safety and Selectivity and Productivity*, 12/01.
40. Engelhard Corporation, Research Center, Iselin, NJ, *NOx Abatement in Diesel Exhaust*, 10/02.
41. Department of Chemical Engineering, UCLA, *New Reactor Types for Improved Safety and Selectivity and Productivity*, 12/02.
42. Department of Chemical Engineering, Northwestern University, *Multi-Functional Catalytic Reactors for Cleaner Energy and Air*, 5/03.
43. Department of Chemical Engineering, Princeton University, *Multi-Functional Catalytic Reactors for Cleaner Energy and Air*, 5/03.
44. Engelhard Corporation, Research Center, Iselin, NJ, *NOx Storage and Reduction Studies*, 5/03.
45. AIChE Gulf Coast Section, Lake Jackson, TX, *Multi-Functional Catalytic Reactors for Cleaner Energy and Air*, 6/03.
46. Department of Chemical Engineering, University of South Carolina, *Multi-Functional Catalytic Reactors for Cleaner Energy and Air*, 9/03.
47. Department of Chemical Engineering, University of Florida, *An Adsorptive Reactor for NOx Reduction*, 12/03.
48. Ford Motor Company, Dearborn, MI, *Performance and Mechanistic Studies of the NOx Trap Reactor for Lean NOx Reduction*, 3/04.
49. Cummins Inc., Columbus, IN, *Performance and Mechanistic Studies of the Lean NOx Trap*, 5/04.
50. Department of Chemical Engineering, University of Pittsburgh, *An Adsorptive Reactor for NOx Reduction*, 12/04.
51. Engelhard Corporation, Research Center, Iselin, NJ, *NOx Storage and Reduction Studies*, 2/05.
52. Department of Chemical Engineering, Case Western, *Multi-Functional Catalytic Reactors for NOx Reduction and Hydrogen Generation*, 3/06.
53. CLEERS Conference, Mechanistic and Kinetics Studies of NOx Storage and Reduction on Model Catalysts, Dearborn, MI, 5/06.
54. Varian Medical Technologies, *Synthesis and Characterization of Pd-Based Hollow Fiber Membranes for Reaction and Separation*, Mountain View, CA, 11/06.
55. Houston Advanced Research Center, *Challenges and Opportunities for Biodiesel in NOx and PM Reduction*, Woodlands, Texas, 12/06.
56. North American Symposium of Chemical Reaction Engineering 2, "Hydrogen Generation and Purification in a High Temperature Pd Hollow Fiber Membrane Reactor," B. Nair, S. Israni, and M. Harold, Houston, TX, 2/07.
57. Department of Chemical Engineering, The University of Texas at Austin, *Multi-Functional Catalytic Reactors for NOx Reduction and Hydrogen Generation*, 2/07.
58. Ford Motor Company, Corporate Research, *Spatio-Temporal Behavior of the Lean NOx Trap*, Dearborn, MI 10/07.
59. Baker-Petrolite Inc., Corporate Research, *Developments in Diesel Emission Control Technology at the University of Houston*, Sugarland, Texas, 10/07.
60. Department of Chemical Engineering, University of Florida, *Spatio-Temporal Behavior of the Lean*

- NOx Trap in Diesel Aftertreatment*, 3/08.
61. Southwest Section of the North American Catalysis Society, *Elucidating Catalytic Chemistry and Spatio-Temporal Phenomena in the Lean NOx Trap*, 4/08.
 62. Department of Mechanical Engineering, University of Houston, *Reduction of NOx from Lean Burn Vehicle Exhaust: Technology Solutions from Simple to Complex*, 2/09.
 63. Division of Research, University of Houston, *Clean Diesel*, 2/09.
 64. CLEERS Working Group, *Mechanistic and Kinetics Studies of NOx Storage and Reduction on Model Catalysts, Isotopic Studies of NOx Storage and Reduction over Pt/BaO/Al₂O₃ Using Temporal Analysis of Products*, 6/09.
 65. AIChE South Texas Section, *Catalytic Solutions to Achieve Clean Diesel Power*, 9/09.
 66. International Conference on Structured Catalysts and Reactors, Ischia, Italy, *A Global Kinetic Model for NOx Storage and Reduction on Pt/BaO/Al₂O₃ Monolithic Catalysts*, 9/09.
 67. Department of Civil and Environmental Engineering, University of Houston, *Catalytic Solutions to Achieve Clean Diesel Power*, 10/09.
 68. Catalysis Society of Michigan, *Catalytic Solutions to Achieve Clean Diesel Power*, 11/09.
 69. Catalysis Club of Greater Chicago, *Catalytic Solutions to Achieve Clean Diesel Power*, 3/10.
 70. Department of Chemical Engineering, University of Southern California, *Multifunctional Catalytic Reactors for Cleaner Energy and Air*, 4/10.
 71. University of Houston, Scholarship and Community Conference, “*Future Outlook for Liquid Transportation Fuels: Diesel or Natural Gas?*” Houston, TX, 4/10.
 72. Fluor Inc., “*Multi-Functional Reactors in Clean Energy Applications*,” Sugarland, TX, April 2010.
 73. University of Houston, Cullen College of Engineering Leadership Board, “*Texas Diesel Testing and Research Center*,” Houston, TX, 4/10.
 74. BASF, “*Studies of Lean NOx Reduction in Diesel Vehicles: From Bench Flow Reactors to Dynamometers*,” Iselin, NJ, 5/10.
 75. Honda Research Institute, “*Enhancing Liquid Fuel Yield During Algae Pyrolysis in Structured Catalytic Reactors*,” Columbus, OH, 7/10.
 76. Cummins Inc., “*Lean NOx Reduction in Diesel Vehicles: Mechanistic and Microkinetics Studies of the Transient Catalysis*,” Columbus, IN, 7/10.
 77. Petroleum Club of Houston, The Lunch and Learn Seminar Series, *Emerging Technologies for Clean Diesel*, Houston, TX, 10/10.
 78. Total Petrochemicals Inc., *Pd Membranes for Process Intensification*, Houston, TX, 3/11.
 79. Catalysis Club of Philadelphia, *Multi-Functional Catalysts and Reactors for Lean NOx Reduction*, Newark, DE, 5/11.
 80. North American Catalysis Society, North American Meeting, and Keynote Lecture: *Probing and Exploiting Interactions between Storage, Reaction and Transport Processes During Lean NOx Reduction*, Detroit, MI, 6/11.
 81. CLEERS Working Group, *Transport and Reaction Coupling During NOx Storage and Reduction and Selective Catalytic Reduction*, 9/11.
 82. Honda Research Institute, *Catalytic Pyrolysis of Microalgae*, Mountain View, CA, 11/11.
 83. Ninth International Congress on Catalytic Air Pollution Control, Keynote Lecture, *Dual Layer Catalysts for Lean Reduction of NOx by in situ Generated Ammonia*, Brussels, Belgium, 8/12.
 84. Caterpillar Inc., *Studies of Selective Catalytic Reduction: From Microkinetics through Vehicle Testing*, Peoria, IL, 9/12.
 85. Cummins Inc., *Studies of Selective Catalytic Reduction, NO Oxidation and NH₃ Oxidation: Reaction and Transport on Structured Catalysts*, Columbus, IN 10/12.
 86. Department of Chemical Engineering, Carnegie Mellon University, *Reduction of NOx from Lean Burn Vehicles: A Challenging Problem in Multi-Functional Catalyst & Reactor Design*, 11/12.
 87. Department of Chemical Engineering, Beijing University of Technology, Beijing, China, *Catalytic Solutions for Lean Reduction of Nitrogen Oxides*, 1/13.

88. Department of Chemical Engineering, Tianjin, China, *Catalytic Solutions for Lean Reduction of Nitrogen Oxides*, Pei Yang University Lectureship, Tianjin University, 1/13.
89. Department of Chemical Engineering, South China University of Science and Technology, Guangzhou, China, *Catalytic Solutions for Lean Reduction of Nitrogen Oxides*, 1/13.
90. Department of Chemical Engineering, Sun Yat Sen University, Guangzhou, China, *Catalytic Solutions for Lean Reduction of Nitrogen Oxides*, 1/13.
91. Department of Chemical Engineering, East China University of Science & Technology, Shanghai, China, *Catalytic Solutions for Lean Reduction of Nitrogen Oxides*, 1/13.
92. Department of Chemical Engineering, University of Alabama, Tuscaloosa, Alabama, *Catalytic Solutions for Lean Reduction of Nitrogen Oxides*, 4/13.
93. Department of Chemical Engineering, Columbia University, New York, NY, *Catalytic Solutions for Lean Reduction of Nitrogen Oxides*, 4/13.
94. Haldor Topsøe Catalysis Forum, Munkerpugaard, Denmark, *Modeling and Simulation of Transient Behavior of Multi-Functional Lean NO_x Catalysts*, 8/13.
95. 3rd International Symposium on Modeling of Exhaust-Gas After-Treatment (Modegat III), Keynote lecture: *Tutorial on NO_x Storage: Modeling and Analysis of Multi-functional Lean NO_x Catalysts*, Bad Herrenalb/Karlsruhe, Germany, 9/13.
96. Global Powertrain Congress, Troy, Michigan, *Catalytic Reduction of NO_x in Lean Burn Engine Exhaust: Emerging Technology Trends*, 10/13.
97. Department of Chemical Engineering, Texas A&M University, College Station, TX, *Catalytic Solutions for Lean Reduction of Nitrogen Oxides*, 11/13.
98. Department of Chemical Engineering, Lamar University, Beaumont, TX, *Catalytic Solutions for Lean Reduction of Nitrogen Oxides*, 2/14.
99. ACS Spring National Meeting, Dallas, Texas, *Selective Catalytic Reduction in Dual Layer Monolithic Catalysts*, 3/14.
100. International Symposium on Chemical Reaction Engineering (ISCRE-23), Keynote lecture: *Multi-Layer Monolith Catalysts for Lean NO_x Reduction*, Bangkok, Thailand, 9/14.
101. Department of Chemical and Biomolecular Engineering, Notre Dame University, South Bend, IN, *Multi-functional Catalysts and Reactors for Reduction of NO_x from Lean Burn Vehicles* 11/14.
102. AIChE Meeting, Atlanta, GA, and Session in Honor of Arvind Varma: Recipient of 2013 Warren K. Lewis Award, *Applied Mathematics and Reaction Engineering: Sustainable Elements of the Chemical Engineering Discipline*, 11/14.
103. AIChE Meeting, Atlanta, GA, Session on Automotive Emission Control, *Multi-Layer Monolith Catalysts for Lean NO_x Reduction*, 11/14.
104. Department of Chemical Engineering, University of Michigan, Ann Arbor, MI, *Multi-Functional Structured Catalysts for Clean Exhaust from Lean Burn Vehicles*, 12/14.
105. Michigan Catalysis Society, *Periodic Storage and Reduction on Structured Catalysts for Lean NO_x Reduction*, Livonia, MI, 12/14.
106. Department of Chemical Engineering, Purdue University, West Lafayette, IN, *Multi-Functional Structured Catalysts for Clean Exhaust from Lean Burn Vehicles*, 4/15.
107. Sino-US Chemical Engineering Conference, *Reaction and Transport Coupling in Multi-Functional Catalysts for Selective Oxidation of Ammonia to Nitrogen*, Keynote Lecture, 10/15.
108. AIChE Annual Meeting, Salt Lake City, Session in Honor of Curtis Conner, *Selective Oxidation of Ammonia on Multi-Layer Cu-SSZ-13 + Pt/Al₂O₃ Monoliths: Impact of Top Layer*, 11/15.
109. AIChE Annual Meeting, Salt Lake City, *Fast Cycling for Enhanced Low-Temperature NO_x Reduction on Dual-Layer NSR + SCR Catalysts*, 11/15.
110. Lube School, Houston, TX, *Catalytic Solutions to Cleaning Diesel Engine Exhaust*, 3/16.
111. "Symposium on Modeling and Optimization of Chemical Processing and Reaction Systems" Kazan, Russia, *Emerging Catalytic Solutions for Lean Burn Engine Exhaust*, 5/16.

112. Department of Chemical Engineering, University of South Florida, Tampa, FL, *Multi-Functional Structured Catalysts for Clean Exhaust from Lean Burn Vehicles*, 11/16.
113. Department of Chemical Engineering, University of Florida, Gainesville, FL, *Multi-Functional Structured Catalysts for Clean Exhaust from Lean Burn Vehicles*, 11/16.
114. Department of Chemical Engineering, Cornell University, Ithaca, NY, *Multi-Functional Structured Catalysts for Clean Exhaust from Lean Burn Vehicles*, 4/18.
115. ISCRE 25, Florence, Italy, *Reaction Engineering of Catalytic Converters for Lean Burn Vehicles: Tailored Catalyst Architectures and Operational Strategies for Enhanced Performance*, (plenary lecture), 5/18.
116. Department of Chemical Engineering, University of Buffalo, Buffalo, NY, *Multi-Functional Structured Catalysts for Emission Control*, 3/19.
117. ICOSCAR ((International Conference on Structured Catalysts and Reactors), Bad Herrenalb, Germany, *Spatiotemporal Studies of Multi-functional Catalysts for Emission Control*, (plenary lecture) 9/19.
118. Department of Chemical Engineering, New York University, New York, NY, *Spatio-temporal Studies of Structured Multi-Functional Catalytic Converters for Emission Control*, 12/19.
119. Southwest Catalysis Society, Award for Excellence in Applied Catalysis, *Catalytic Engineering Studies of NH₃ Oxidation on Platinum*, 6/20.
120. Advanced Combustion and Emission Control, *Catalytic Oxidation of NH₃ for Slip Control*, 9/20.
121. Department of Chemical Engineering, Queens University Belfast, *Catalytic Engineering Studies of NH₃ Oxidation on Platinum*, 10/20.
122. Umicore, Research Division, *Catalytic Engineering Studies of NH₃ Oxidation on Platinum*, 3/21.
123. American Chemical Society, 2021 Fall Meeting, Environmental Division, Sub-Stoichiometric Methane Oxidation on Structured Pt/Pd + Mixed Metal Oxide Spinel: Mechanistic Origins of Rate Multiplicity and Enhancement during Feed Modulation, 8/21.
124. CLEERS Working Group, *Coupled Uptake and Conversion of NO_x and Reductants on Pd/SSZ-13: Experiments and Modeling*, 10/21.
125. Performatica Webinar, Panelist for Methane, the Other Greenhouse Gas: Challenges and Opportunities, 11/21.
126. Department of Chemical Engineering, *Catalytic Oxidation of Methane, the Other Greenhouse Gas*, Northeastern University, 12/21.
127. Twelfth International Congress on Catalytic Air Pollution Control, Keynote Lecture, Spatiotemporal Features of NO and Hydrocarbons Trapping and Conversion in a PNA + HCT + OC Sequential Monolith Configuration, Brussels, Belgium, 8/22.
128. AIChE Annual Meeting, The Catalysis and Reaction Engineering Division at 25 Years: Achieving the Vision, CRE Division Dinner, Phoenix, AZ, 11/22.
129. AIChE Annual Meeting, Spatiotemporal Features of Environmental Catalysts, Session in Honor of V. Balakotaiah, Phoenix, AZ, 11/22.
130. American Chemical Society, Methane oxidation on Pt/Pd/Al₂O₃ monolith catalysts: Kinetics, multiplicity, spatial features and feed modulation enhancement, 2023 Fall Meeting, 8/23.

Conference Presentations

1. "An Experimental Study of the Multiplicity Features of the Catalytic Oxidation of Carbon Monoxide and Ethane on Pt/Al₂O₃," 1982 Annual AIChE Meeting, Los Angeles, CA, 11/82 (with D. Luss).
2. "Kinetic Parameter Estimation by the Fitting of Bifurcation Points: Ethane Oxidation on Pt/ Pt/Al₂O₃," 1986 Annual AIChE Meeting, Miami, FL, 11/86 (with D. Luss).
3. "Kinetic Model Discrimination and Parameter Estimation for Catalytic Reactions Exhibiting Steady-State Multiplicity," Third Research Symposium of the Catalysis Society of New England, Worcester, MA, 11/86.
4. "Surface Analyses and Modeling of Rate Multiplicity and Oscillations," Surface Science and Catalysis Symposium of DOE Basic Energy Sciences, National Bureau of Standards, Gaithersburg, MD, 10/87

- (poster; with M. Garske, D. Sullivan, and W.C. Conner).
5. "Effectiveness Enhancement and Reactant Depletion in a Partially Wetted Catalyst," 1987 Annual AIChE Meeting, New York, NY, 11/87 (with K. M. Ng).
 6. "Effectiveness of a Partially Wetted Catalyst," 1987 Annual AIChE Meeting, New York, NY, 11/87 (with G.A. Funk and K.M. Ng).
 7. "The Catalytically Impregnated Hollow Fiber Reactor," 1988 Annual AIChE Meeting, Washington D.C., 12/88 (with P. Cini, B. Patenaude, and K. Venkataraman).
 8. "Effect of Flow Distribution on Reaction in Trickle-Bed Reactors," 1988 Annual AIChE Meeting, Washington D.C., 12/88 (with G.A. Funk and K.M. Ng).
 9. "Exothermic Reaction in the Incompletely Wetted and Filled Catalytic Pellet: Imbibition, Vaporization, and Multiplicity," 1988 Annual AIChE Meeting, Washington D.C., 12/88 (with P. Watson).
 10. "Rate Multiplicity for Carbon Monoxide Oxidation on a Platinum Wire," North American Catalysis Society Meeting, Dearborn, Michigan, 5/89 (with M. Garske).
 11. "The Catalytic Ceramic Tube as a Multiphase Reactor," North American Membrane Society National Meeting, Austin, Texas, 5/89 (with P.Cini and K. Venkataraman).
 12. "A Simple Methodology for Predicting Cross-Sectional Shapes of Locally Grown GaAs," 1989 Electronic Materials Conference, Cambridge, Massachusetts (with S. Jones and K. M. Lau).
 13. "An Experimental Study of a Multiphase Reaction in a Single, Partially Wetted Catalytic Pellet," 1989 Annual AIChE Meeting, San Francisco, CA, 11/89 (with G.A. Funk and K.M. Ng).
 14. "On the Causes of Rate Multiplicity in CO Oxidation on Pt. The Impact of Total Pressure," 1989 Annual AIChE Meeting, San Francisco, CA, 11/89 (with M.E. Garske).
 15. "Preparation and Characterization of the Catalytic Ceramic Tube for Use as a Multiphase Catalyst," 1989 Annual AIChE Meeting, San Francisco, CA, 11/89 (with P. Cini, S. Blaha, and K. Venkataraman).
 16. "The Tubular Supported Ceramic Membrane as a Multiphase Catalyst," International Congress on Membranes, Chicago, 8/90 (with P. Cini and K. Venkataraman).
 17. "Impact of Temperature Nonuniformities on Rate Multiplicity Features During CO Oxidation on an Electrically Heated Wire," presented in 'Chemical Reactor Stability and Dynamics' session, Annual AIChE Meeting, Chicago, 11/90 (with M.E. Garske).
 18. "Surface Analysis with FTIR Emission Spectroscopy," presented in 'General Papers in Catalysis II' session, Annual AIChE Meeting, Chicago, 11/90 (with D. Sullivan and W.C. Conner).
 19. "Preparation and Characterization of Alumina and Silica-Alumina Tubular Membranes for Use as Catalyst Supports," presented in 'Preparation and Characterization of Membrane Structures, session, Annual AIChE Meeting, Chicago, 11/90 (with P. Cini and R. Seymour).
 20. "Exothermic Multiphase Reaction with Vaporization in the Single Catalytic Pellet: Modeling and Experiment," presented in 'Novel Reactor Techniques for Heterogeneous Systems,' session, Annual AIChE Meeting, Chicago, 11/90 (with P. Watson).
 21. "Dynamic and Steady-State Behavior of a Single Catalytic Pellet During and Exothermic Multiphase Reaction," North American Catalysis Society Conference, Lexington, Kentucky, 5/91 (poster; with P. Watson).
 22. "Improving Partial Oxidation Product Yield with a Catalytic Inorganic Membrane," North American Membrane Society Annual Meeting, Lexington, Kentucky, 5/92 (with V.T. Zaspalis, K. Keizer, and A. Burggraaf).
 23. "Kinetics and Dynamics Studies of Oxidation Reactions Involving an Adsorbed CO Species," Surface Science and Catalysis Symposium of DOE Basic Energy Sciences, Santa Monica, CA (poster; with W.C. Conner).
 24. "Kinetics and Dynamics Studies of Oxidation Reactions Involving an Adsorbed CO Species," Review of DOE-Sponsored Catalysis Research, Gaithersburg, MD (with W.C. Conner).
 25. "Vaporization Effects During an Exothermic Multiphase Reaction in a Catalytic Pellet," Gordon Conference on Catalysis, 6/92 (poster; with P. Watson).

26. "Monitoring Oxidation-Reduction During Reaction with FTIR Emission Spectroscopy: Ethylene Oxidation on V_2O_5 ," presented in 'Fundamentals of Oxide Catalysts' session, Annual AIChE Meeting, Miami, 11/92 (with D. Sullivan and W.C. Conner).
27. "Steady-State and Dynamic Pore Emptying Effects During Multiphase Reaction in a Single Catalytic Pellet," presented in 'General Papers in Reaction Engineering' session, Annual AIChE Meeting, Miami, 11/92 (poster; with P. Watson).
28. "Vaporization Induced External Dewetting of a Catalyst During an Exothermic Multiphase Reaction," presented in 'Multiphase Reactors' session, Annual AIChE Meeting, Miami, 11/92 (with K.M. Ng).
29. "Steady-State and Dynamic Pore Emptying Effects During Multiphase Reaction in a Single Catalytic Pellet," presented at Engineering Foundation Meeting 'Chemical Reaction Engineering: The Core Components,' Palm Coast, Florida, 2/93 (poster; with P. Watson).
30. "Vaporization in the Partially Wetted Catalytic Pellet: Linking Theory and Experiment," presented in 'Experimental Verification of Multiphase Reaction Engineering Models' session, Annual AIChE Meeting, St. Louis, 11/93 (with P. Kharbanda and P.C. Watson).
31. "Solid State Catalyst Transformations During Oxidation Reactions Over Vanadium Oxide," presented in 'Kinetics, Catalysis, and Reaction Engineering' session, Annual AIChE Meeting, San Francisco, 11/94 (poster; with D. Sullivan and W.C. Conner).
32. "Alternate Reactor Types and Feed Configurations for Intermediate Yield Improvement in Consecutive-Parallel Reaction Systems," presented at ISCRE 13, Baltimore, 9/94 (with C. Lee, T. Leib, and J. Lerou).
33. "Nonpermselective Inorganic Membrane Reactors for Rate and Yield Enhancement in Catalysis," presented at Philadelphia Catalysis Society, Spring Symposium, Newark, DE, 5/95.
34. "Use of Nonpermselective Membrane Reactors in Consecutive-Parallel Catalytic Reaction Networks," presented in 'Catalytic Reaction Engineering' session, 14th North American Catalysis Society Meeting, Snowbird, 6/95 (with C. Lee and K. M. Ng).
35. "Solid-State Catalyst Transformations During Oxidation Reactions Over Vanadium Oxide," presented in 'Catalyst Characterization' session, 14th North American Catalysis Society Meeting, Snowbird, 6/95 (with D. Sullivan, presenter, and W.C. Conner).
36. "The Continuously-Stirred Decanting Reactor: Steady-State and Dynamic Features," ISCRE 14, Brugge, 5/96 (with J.J. Ostermaier, D.W. Drew, J.J. Lerou, and D. Luss).
37. "Micromachined Chemical Reactors for Surface Catalyzed Oxidation Reactions," IEEE Solid-State Sensor and Actuator Workshop, Hilton Head, SC, 1996 (with Srinivasan, R., presenter, I-M. Hsing, J. Ryley, K.F. Jensen, and M.A. Schmidt).
38. "Simulations of Micromachined Chemical Reactors," IEEE Solid-State Sensor and Actuator Workshop, Hilton Head, SC, 1996 (with Srinivasan, R., I-M. Hsing, presenter, J. Ryley, K.F. Jensen, and M.A. Schmidt).
39. "Pneumatically Controlled Multicomponent Transport in Inorganic Membrane Reactors," International Symposium on Inorganic Membranes, Gatlinburg, 7/96 (with V. Papavassiliou and J. Nestlerode).
40. "Metal-Supported Carbogenic Membranes: Synthesis and Applications," International Symposium on Inorganic Membranes, Gatlinburg, 7/96 (with M. Acharya, presenter, and H. Foley).
41. "Microreactors for Safe Manufacture of Hazardous Materials," presented in 'Reaction Engineering for Environmentally Clean Processes' session, Annual AIChE Meeting, Chicago, 11/96 (with J. Lerou, presenter, and J. Ryley).
42. "Micromachined Chemical Reactors for Partial Oxidation Reactions," presented in 'Reaction Engineering for Environmentally Clean Processes' session, Annual AIChE Meeting, Chicago, 11/96 (with R. Srinivasan, presenter, I-M. Hsing, K. Jensen, M. Schmidt, and J. Ryley).
43. "Simulation of Micromachined Chemical Reactors for Heterogeneous Oxidation Reactions," presented in 'Fundamental Chemical and Physical Processes in Combustion and Incineration' session, Annual AIChE Meeting, Chicago, 11/96 (with I-M. Hsing, presenter, R. Srinivasan, K. Jensen, M. Schmidt, and J. Ryley).

44. "The Effect of Reactor Geometry on Gas Phase Ignition and Free Radical Profiles in Heterogeneous Oxidation Reactions," presented in 'Dynamics of Chemical Reactors II' session, Annual AIChE Meeting, Chicago, 11/96 (with I-M. Hsing, presenter, K. Jensen, R. Srinivasan, and M. Schmidt).
45. "Supported Carbogenic Molecular Sieve Membranes - Synthesis and Applications in Gas Separations," presented in 'Synthesis of Ceramic Films and Membranes' session, Annual AIChE Meeting, Chicago, 11/96 (with M. Acharya, presenter, and H. Foley).
46. "Pneumatically- Controlled Multicomponent Transport and Reaction in Inorganic Membrane Reactors," presented in 'Synthesis of Ceramic Films and Membranes' session, Annual AIChE Meeting, Chicago, 11/96 (with V. Papavassiliou).
47. "Steady State and Dynamic Features of the Continuously-Stirred Decanting Reactor," presented in 'Experimental Verification of Multiphase Reaction Engineering Models' session, Annual AIChE Meeting, Chicago, 11/96 (with J. Khinast, D. Luss, and J. Ostermaier).
48. "Reaction Engineering for Microreactor Systems," 1st International Conference on Microreactor Technology, DECHEMA e.V., Frankfurt am Main, Germany, 1997 (with Jensen, K.F., I-M. Hsing, presenter, R. Srinivasan, M.A. Schmidt, J.J. Lerou, and J.F. Ryley).
49. "The Influence of CeO₂ on Propylene and Propane Total Oxidation over Pt/ CeO₂/Al₂O₃ Catalysts," presented at North American Catalysis Society Meeting, Chicago, 5/97 (with A. Oliviero, presenter, and W. C. Conner).
50. "Chemical Performance and High Temperature Characterization of Micromachined Chemical Reactors" Ninth International Conference on Solid-State Sensors and Actuators, Chicago, 1997 (with Srinivasan, presenter, R., S.L. Firebaugh, I-M. Hsing, J. Ryley, K.F. Jensen, and M.A. Schmidt).
51. "Finite Element Simulation Strategies for Microfluidic Devices with Chemical Reactions," Ninth International Conference on Solid-State Sensors and Actuators, Chicago, 6/97 (with I-M. Hsing, presenter, R. Srinivasan, K.F. Jensen, and M. Schmidt).
52. "Steady State Behavior of the Boiling Slurry Reactor," presented at Annual AIChE Meeting, Los Angeles, 11/97 (with J. Khinast, presenter, T. Leib, and D. Luss).
53. "Multicomponent Transport in Carbogenic Molecular Sieve Membranes," presented at Annual AIChE Meeting, Los Angeles, 11/97 (with M. Acharya, presenter, and H.C. Foley).
54. "Reaction Engineering Analysis for Microchemical Systems," presented at Annual AIChE Meeting, Los Angeles, 11/97 (with I-M. Hsing, presenter, R. Srinivasan, K. Jensen, and M. Schmidt).
55. "Micromachined Chemical Reactors for Heterogeneously Catalyzed Partial Oxidation Reactions," presented at Annual AIChE Meeting, Los Angeles, 11/97 (with R. Srinivasan, presenter, T. Floyd, I-M. Hsing, K. Jensen, M. Schmidt, and J. Ryley).
56. "The Influence of Axial Dispersion on the Stability of a Boiling Slurry Reactor," presented at Annual AIChE Meeting, Dallas, 11/99 (with J. Khinast, presenter, D. Luss, and T. Leib).
57. "High Purity Hydrogen from Methanol in a Catalytic Membrane Reactor: A Feasibility Study," presented at Annual AIChE Meeting, Reno, 11/01 (with G. Kolios).
58. "Perspectives on Industrial Collaborations and Sponsored Research," presented at Annual AIChE Meeting, Reno, 11/01.
59. "Membrane Fuel Processor for Hydrogen Generation: Reactor and Process Issues," presented at ACS Meeting, Boston, 8/02.
60. "Spatially Averaged Models for Multiphase Chemical Reactors," presented at Annual AIChE Meeting, Indianapolis, 11/02 (with M. Bhattacharya and V. Balakotaiah).
61. "Shape Normalization for Catalytic Reactors," presented at Annual AIChE Meeting, Indianapolis, 11/02 (poster; with M. Bhattacharya, presenter, and V. Balakotaiah).
62. "Integrated Reaction Systems for Hydrogen Generation: Reactor and Process Issues," presented at Annual AIChE Meeting, Indianapolis, 11/02 (with J. Lattner and G. Kolios).
63. "Catalytic Engineering Studies of NO_x Storage and Reduction," presented at North American Catalysis Meeting, Cancun, Mexico, 6/03 (with R. Muncrief and K. Coym).
64. "Low Dimensional Models for Gas-Liquid Reactors," presented at AIChE Meeting, San Francisco,

- 11/03 (with M. Bhattacharya, presenter, and V. Balakotaiah).
65. "Steady-State and Transient Studies of NO_x Storage and Reduction in a Monolith Converter," presented at AIChE Meeting, San Francisco, 11/03 (with K. Kabin, presenter, and R. Muncrief).
 66. "Mechanistic Studies of NO_x Storage and Reduction" presented at AIChE Meeting, San Francisco, 11/03 (with and R. Muncrief, presenter, and K. Kabin).
 67. "Comparison of Conventional and Membrane Reactor Fuel Processors for PEM Fuel Cell Systems Using Hydrocarbon and Methanol Fuels," presented at AIChE Meeting, San Francisco, 11/03 (with J. Lattner, presenter).
 68. "Mass/Heat Transfer Coefficients in Monoliths with Washcoat Diffusion", presented at AIChE Meeting, San Francisco, 11/03 (with M. Bhattacharya, presenter, and V. Balakotaiah).
 69. "Dynamics of Storage and Reaction in a Monolith Reactor: Lean NO_x Reduction," presented at ISCRE Meeting, Chicago, 6/04 (poster; with K. Kabin, presenter, R. Muncrief, and Y. Li).
 70. "Low Dimensional Models for Homogeneous and Multiphase Stirred Tank Reactors," presented at ISCRE Meeting, Chicago, 6/04 (with M. Bhattacharya, presenter, and V. Balakotaiah).
 71. "NO_x Storage and Reduction in Catalytic Monoliths", presented at AIChE Meeting, Austin, 11/04 (with M. Sharma, presenter, and V. Balakotaiah).
 72. "Synthesis and Characterization of Supported Pd Hollow Fiber Ceramic Membranes", presented at AIChE Meeting, Austin, 11/04 (with Balamurali Nair, presenter).
 73. "Modeling of NO_x Storage and Reduction for Diesel Exhaust Emission Control," presented at Society of Automotive Engineers World Congress, Detroit, MI (2005). (With M. Sharma, presenter, K Kabin, and V. Balakotaiah)
 74. "TAP Studies of NO_x Storage and Reduction: Elucidating the Kinetics and Mechanism on Model Pt/BaO/Alumina Catalysts," presented at North American Catalysis Society Meeting, Philadelphia (May 2005). (with P. Khanna, K. Kabin, and V. Medhekar).
 75. "Methanol Autothermal Reforming in a Dual Membrane Reactor," at North American Catalysis Society Meeting, Philadelphia (May 2005) (with J. Lattner, presenter, and B. Nair).
 76. "Modeling of NO_x Storage and Reduction for Diesel Exhaust Emission Control," to be presented at Society of Automotive Engineers World Congress, San Antonio, TX (October 2005). (with M. Sharma, presenter, and V. Balakotaiah).
 77. "Development of Encapsulated Submicron Pd & Pd/Ag Alloy Hollow Fiber Membranes for a Membrane Fuel Processor," presented at AIChE Meeting, Cincinnati, 11/05 (with Balamurali Nair, presenter).
 78. "Hydrogen from Methanol in a Dual Membrane ATR Reactor," presented at AIChE Meeting, Cincinnati, 11/05 (with Jim Lattner and Balamurali Nair).
 79. "Periodic NO_x Storage and Reduction (NSR) for Lean Burn Engines", presented at AIChE Meeting, Cincinnati, 11/05 (with Manish Sharma and Vemuri Balakotaiah).
 80. "TAP and Bench-Scale Reactor Studies of NO_x Storage and Reduction on Model Pt/BaO/Al₂O₃ and Pt/Al₂O₃," presented at AIChE Meeting, Cincinnati, 11/05 (with Vinay Medhekar, presenter, Pranav Khanna, and Vemuri Balakotaiah).
 81. "Experimental Analysis and Mathematical Modeling of NO_x Storage and Reduction," poster presented at the Spring 2006 Symposium of the Southwest Catalysis Society, Rice University, 5/06 (with Vinay Medhekar, presenter, and Vemuri Balakotaiah).
 82. "Multiplicity in Lean NO_x Traps," poster presented at the International Symposium of Chemical Reaction Engineering, Berlin, and Germany, 9/06 (with Manish Sharma, Robert Clayton, and Vemuri Balakotaiah, presenter).
 83. "Modeling and Experimental TAP Studies on the Kinetics of NO_x Storage and Reduction over Pt/Al₂O₃ and Pt/BaO/Al₂O₃ Catalysts," presented at the AIChE National Meeting, San Francisco, CA, 11/06 (with Vinay Medhekar and Vemuri Balakotaiah).
 84. "Steady State and Dynamic Studies of NO_x Storage and Reduction with H₂ on Pt/BaO/Al₂O₃ Monoliths," presented at the AIChE National Meeting, San Francisco, CA, 11/06 (with Robert Clayton,

- speaker, and Vemuri Balakotaiah).
85. "Modeling of NO_x Storage and Reduction in Catalytic Monolith Reactors," presented at the AIChE National Meeting, San Francisco, CA, 11/06 (with Jin Xu, speaker, and Vemuri Balakotaiah).
 86. "Encapsulated Pd Composite Hollow Fiber Membrane: Permeation and Reaction Studies," presented at the AIChE National Meeting, San Francisco, CA, 11/06 (with Balamurali Nair).
 87. "Mechanistic Investigation of NSR (Nitrogen Oxide Storage and Reduction) Catalysts," presented at the AIChE National Meeting, San Francisco, CA, 11/06 (with Karen Kabin, Su Yu and Michael Amiridis).
 88. "Ammonia Formation During Steady-State and Cyclic Operation of the NO_x Trap with H₂ as the Reductant," Clayton, R., V. Balakotaiah, and M. Harold, NASCRE 2, Houston, TX, 2/07.
 89. "Determination of the Microkinetics of NO_x Storage and Reduction on Pt/BaO/Al₂O₃ Catalysts Using TAP," Medhekar, V., V. Balakotaiah, and M. Harold NASCRE 2, Houston, TX, 2/07.
 90. "Ammonia and Nitrous Oxide Formation during NO_x Storage and Reduction on Pt/Ba Monolith Catalysts," North American Catalysis Society Conference, Houston, Texas, 6/07 (with Robert Clayton, presenter, and Vemuri Balakotaiah).
 91. "Microkinetic Model Development of NO_x Storage and Reduction over Pt/BaO/Al₂O₃ Catalyst using Temporal Analysis of Product Reactor," North American Catalysis Society Conference, Houston, Texas, 6/07 (with Ashok Kumar, presenter, Vinay Medhekar, and Vemuri Balakotaiah).
 92. "Hydrogen Generation and Purification in Pd Nanopore Hollow Fiber Membrane Reactor," ACS Fuel Division, presented at ACS 2007 National Meeting, Division of Fuel Chemistry, Boston, MA, 8/07 (with S. H. Israni).
 93. "Nanopore Membrane Based Reactors for Production of High Purity Hydrogen from Ammonia and Methanol," presented at the AIChE National Meeting, Salt Lake City, UT, 11/07 (with Balamurali Nair and Sameer Israni, presenter).
 94. "Microkinetic Model Development for NO_x Storage and Reduction Over Pt/Ba/Al₂O₃ Catalysts Using Temporal Analysis of Products," presented at the AIChE National Meeting, Salt Lake City, UT, 11/07 (with Ashok Kumar, presenter and Vemuri Balakotaiah).
 95. "Towards Optimal NO_x Trap Operation," presented at the AIChE National Meeting, Salt Lake City, UT, 11/07 (with Robert Clayton and Vemuri Balakotaiah).
 96. "Low-Dimensional Models for Bifurcation Analysis of Catalytic Monolith Reactors," presented at the AIChE National Meeting, Salt Lake City, UT, 11/07 (with Saurabh Joshi, presenter, and Vemuri Balakotaiah).
 97. "Microkinetic Modeling of Steady-State NO Reduction by H₂ on Pt/Ba/Al₂O₃ Monolith Catalysts," presented at the AIChE National Meeting, Salt Lake City, UT, 11/07 (poster; with Jin Xu and Vemuri Balakotaiah, presenter).
 98. "Averaged Multi-Mode Models for Multiphase Catalytic Reactors," presented at the AIChE National Meeting, Salt Lake City, UT, 11/07 (poster; with Saurabh Joshi, presenter, and Vemuri Balakotaiah).
 99. "Optimal Design of Three-Way Catalytic Converters to Reduce Cold Start Emissions," presented at the AIChE National Meeting, Salt Lake City, UT, 11/07 (poster; with Divesh Bhatia, presenter, and Vemuri Balakotaiah).
 100. "Spatio-Temporal Behavior of NO_x Storage and Reduction Monolith Catalysts," CLEERS Meeting, Dearborn, MI, 5/08 (with R.D. Clayton, A. Kumar, J. Xu, D. Bhatia, and V. Balakotaiah, speaker).
 101. "Bifurcation Analysis of CO and H₂ Oxidation on Pt/Al₂O₃ Monolith Reactors," ISCRE 20 Kyoto, Japan, 8/08 (poster; with D. Bhatia, presenter, V. Balakotaiah).
 102. "External and Internal Mass Transfer Coefficients in Washcoated Catalytic Monolith Reactors," ISCRE 20, Kyoto, Japan, 8/08 (poster; with S. Joshi, presenter, V. Balakotaiah).
 103. "Microkinetic Modeling of Steady-State NO/H₂/O₂ on Pt/BaO/Al₂O₃ NO_x Storage and Reduction Monolith Catalysts: The Role of NH₃," presented at the AIChE National Meeting, Philadelphia, PA, 11/08 (with Jin Xu, presenter, and Vemuri Balakotaiah).
 104. "Elucidating the Role of the Pt/Ba Interface During NO_x Storage and Reduction on Model

- Pt/BaO/Al₂O₃ Catalyst,” presented at the AIChE National Meeting, Philadelphia, PA, 11/08 (with Ashok Kumar, presenter, and Vemuri Balakotaiah).
105. “High Purity Hydrogen Generation from Methanol Steam Reforming Using Pd-Based Membrane Reactors,” presented at the AIChE National Meeting, Philadelphia, PA, 11/08 (with Sameer Israni, presenter).
 106. “Bifurcation Analysis of CO and H₂ Oxidation on Pt/Al₂O₃ Monolith Reactors,” presented at the AIChE National Meeting, Philadelphia, PA, 11/08 (poster; with Divesh Bhatia, presenter, and Vemuri Balakotaiah).
 107. “Multi-Mode Low-Dimensional Models for Real Time Simulations of Monolithic Catalytic Reactors,” presented at the AIChE National Meeting, Philadelphia, PA, 11/08 (poster; with Saurabh Joshi, presenter, and Vemuri Balakotaiah).
 108. “Modeling of Spatio-Temporal Effects in a Lean NO_x Trap Using Global Kinetics,” presented at the AIChE National Meeting, Philadelphia, PA, 11/08 (with Divesh Bhatia, presenter, V. Balakotaiah).
 109. “Elucidating the Mechanism of NO_x Storage and Reduction,” CLEERS Conference, Dearborn, MI, 4/09.
 110. “Experimental and Kinetic Investigations of NO_x reactions on Model Pt Catalysts,” North American Catalysis Society Meeting, San Francisco, CA, 6/09 (with D. Bhatia, speaker; R. McCabe, V. Balakotaiah).
 111. “Isotopic Studies of NO_x Storage and Reduction over Pt/BaO/Al₂O₃ using Temporal Analysis of Products,” North American Catalysis Society Meeting, San Francisco, CA, 6/09 (with A. Kumar, speaker; R. V. Balakotaiah).
 112. “Methanol Steam Reforming in Pd-Ag Membrane Reactor,” presented at the AIChE National Meeting, Nashville, TN 11/09 (with Sameer Israni, presenter).
 113. “Effects of Rh, CeO₂ and Regeneration Conditions During NO_x Storage and Reduction on Pt/Rh/BaO/CeO₂ Monolith Catalysts,” presented at the AIChE National Meeting, Nashville, TN, 11/09 (with Y. Ren, R. Clayton, V. Balakotaiah).
 114. “Bench-Top Engine System for Fast Screening of Alternative Fuels and Fuel Additives,” presented at the AIChE National Meeting, Nashville, TN, 11/09 (with H. An, R. Muncrief, M. Cruz, C. Rooks, and H. Ismail).
 115. “Isotopic Studies of NO_x Storage and Reduction Over Pt/BaO/Al₂O₃ Using Temporal Analysis of Products,” presented at the AIChE National Meeting, Nashville, TN, 11/09 (with A. Kumar, presenter, V. Balakotaiah).
 116. “Modeling of Spatio-Temporal Effects in a Lean NO_x Trap Using Global Kinetics,” presented at the AIChE National Meeting, Nashville, TN, 11/09 (with D. Bhatia, presenter, V. Balakotaiah).
 117. “Low-Dimensional Models for Real Time Simulations of Catalytic Monoliths,” presented at the AIChE National Meeting, Nashville, TN, 11/09 (poster; with Saurabh Joshi, presenter, V. Balakotaiah).
 118. “Internal Mass Transfer Coefficients for Modeling Multi-Component Diffusion and Reaction in Washcoated Catalytic Monoliths,” presented at the AIChE National Meeting, Nashville, TN, 11/09 (with Saurabh Joshi, presenter, V. Balakotaiah).
 119. “Modeling of Spatio-Temporal Effects in a Lean NO_x Trap Using Global Kinetics,” presented at the AIChE National Meeting, Nashville, TN, 11/09 (poster; with D. Bhatia, presenter, V. Balakotaiah).
 120. “Effect of Reactant and Product Gases On Membrane Flux During Methanol Steam Reforming in a Packed Bed Membrane Reactor: Surface Coverage Effects,” presented at the AIChE National Meeting, Nashville, TN, 11/09 (poster; with Sameer Israni, presenter).
 121. “Selective Catalytic Reduction of NO_x With NH₃ On Fe-Zeolite Based Catalysts,” CLEERS Meeting, Dearborn, MI 4/10.
 122. “Microkinetic Modeling of NO_x Storage and Reduction with H₂ as the Reductant,” ISCRE 21, Philadelphia, PA 6/10 (with J. Xu, A. Kumar, V. Balakotaiah).
 123. “Steam Reforming and Ammonia Decomposition in Pd-Based Membrane Reactors: Experiments and Modeling,” ISCRE 21, Philadelphia, PA 6/10 (with S. Israni).

124. "Estimation of Effective Diffusivity of Stored NO_x in the Barium Phase of Pt/BaO/Al₂O₃ Catalyst Using TAP," ISCRE 21, Philadelphia, PA 6/10 (poster with A. Kumar (presenter) and V. Balakotaiah).
125. "Analysis of Traveling Concentration and Thermal Fronts in a Lean NO_x Trap," ISCRE 21, Philadelphia, PA 6/10 (poster with A. Kumar (presenter) and V. Balakotaiah).
126. "Theoretical and Experimental Investigation of Controlling Regimes in Catalytic Monoliths," ISCRE 21, Philadelphia, PA 6/10 (poster with S. Joshi (presenter), Y. Ren, and V. Balakotaiah).
127. "Development of Optimal Catalyst Designs and Operating Strategies for Lean NO_x Reduction in Coupled LNT-SCR Systems," DEER Conference, Detroit, Michigan 9/10 (poster with M. Crocker, R. McCabe, M. Dearth, J. Theis, V. Balakotaiah, D. Luss, C.Z. Wan, and J.S. Choi).
128. "Emerging Technology Retrofit Demonstration Projects," DEER Conference, Detroit, Michigan 9/10 (poster with R. Muncrief (presenter), E. Allison, M. Cruz, and C. Rooks).
129. "Pyrolysis of Microalgae for the Production of Renewable Fuels," presented at AIChE National Meeting, Salt Lake City, 11/10 (with A. Campanella, presenter).
130. "Combustion and Emissions Analysis of Alternative Diesel Fuels in a Compression Ignition Engine," presented at the AIChE National Meeting, Salt Lake City, 11/10 (with G. Bugosh, presenter, R. Muncrief).
131. "Kinetic and Mechanistic Studies of Selective Catalytic Reduction of NO_x on Fe-Zeolite Monolithic Catalysts," presented at the AIChE National Meeting, Salt Lake City, 11/10 (with P. Metkar, presenter, R. Muncrief, V. Balakotaiah).
132. "Steady-state Reactions of NO, CO and H₂O on Pt-Ba/Al₂O₃ Monolith," presented at the AIChE National Meeting, Salt Lake City, 11/10 (with P. Dasari, presenter, R. Muncrief).
133. "Multi-Fiber Pd-Based Membrane Reactor Design for Generating High Purity H₂: Methanol Steam Reforming and Ammonia Decomposition," presented at the AIChE National Meeting, Salt Lake City, 11/10 (with S. Israni).
134. "TAP Studies of NO_x Reduction Using H₂ and NH₃," presented at the AIChE National Meeting, Salt Lake City, 11/10 (with A. Kumar, V. Balakotaiah).
135. "Effect of Pt Dispersion on Observed Kinetics During Oxidation of H₂ On Pt/Al₂O₃ Monolithic Catalyst," presented at the AIChE National Meeting, Salt Lake City, 11/10 (with S. Joshi, V. Balakotaiah).
136. "Effect of Pt Dispersion on Observed Kinetics: Oxidations of Methane and Propylene On Pt/Al₂O₃ Monolithic Catalyst," presented at the AIChE National Meeting, Salt Lake City, 11/10 (with V. Balakotaiah, presenter, S. Joshi).
137. "Determination of Controlling Regimes in Catalytic Monoliths," presented at the AIChE National Meeting, Salt Lake City, 11/10 (poster; with V. Balakotaiah, presenter, S. Joshi).
138. "Pyrolysis of Microalgae for the Production of Renewable Fuels," presented at the Spring National Meeting of ACS, Anaheim, 3/11 (with A. Campanella, presenter).
139. "TAP Studies of NO_x Reduction," presented at the Spring National Meeting of ACS, Anaheim, 3/10 (with X. Zheng, A. Kumar, V. Balakotaiah).
140. "Kinetic and Mechanistic Studies of Selective Catalytic Reduction of NO_x on Cu- and Fe-Zeolite Monolithic Catalysts," presented at the North American Catalysis Society Meeting, Detroit, 6/11 (with P. Metkar, presenter, V. Balakotaiah).
141. "Steady-State Reactions of NO, CO and H₂O on Pt-Ba/Al₂O₃ Monolith," presented at the North American Catalysis Society Meeting, Detroit, 6/11 (with P. Dasari, presenter, R. Muncrief).
142. "Spatio-temporal Features of Periodic Oxidation of H₂ and CO on Pt/CeO₂/Al₂O₃," CLEERS, Dearborn, MI, 4/11 (with Y. Liu and D. Luss).
143. "Pyrolysis of Microalgae for the Production of Renewable Fuels," poster presented at International Conference on Algal Biomass, Biofuels and Bioproducts, St. Louis, 7/11 (with A. Campanella).
144. "Catalytic Pyrolysis of Microalgae for the Production of Renewable Fuels," presented at AIChE Annual Meeting, Minneapolis, 10/11 (with A. Campanella).

145. "Experimental and Kinetic Modeling Study of Selective Catalytic Reduction of NO_x on Fe- and C-Based Zeolitic Monolithic Catalysts, presented at AIChE Annual Meeting, Minneapolis, 10/11 (with P. Metkar, presenter, and V. Balakotaiah).
146. "Modeling the Effect of Pt Dispersion During Steady-State NO Oxidation and Transient NO_x Storage and Regeneration on Pt/BaO/Al₂O₃ Lean NO_x Trap Catalysts," presented at AIChE Annual Meeting, Minneapolis, 10/11 (with B. Shakya, presenter, and V. Balakotaiah).
147. "NO_x Storage and Reduction by Multilayer Monolithic Catalysts," presented at AIChE Annual Meeting, Minneapolis, 10/11 (with Y. Liu presenter, and D. Luss).
148. "Studies of NH₃ Formation over Pt/BaO/Al₂O₃ LNT Monoliths in the Presence of Excess Water," presented at AIChE Annual Meeting, Minneapolis, 10/11 (with P. Dasari and R. Muncrief).
149. "Determination of Controlling Regimes for Various SCR Reactions on Zeolitic-Based Monolithic Catalysts," poster presented at AIChE Annual Meeting, Minneapolis, 10/11 (with P. Metkar, presenter, and V. Balakotaiah).
150. "NO_x Reduction in Dual-Layer LNT/SCR Catalysts," CLEERS, Dearborn, MI, 4/12 (with Y. Liu and D. Luss).
151. "Ammonia Oxidation on Structured Catalysts," Ninth International Congress on Catalytic Air Pollution Control, Brussels, Belgium, 9/12 (with S. Shrestha, K. Kamasamudram, and A. Yezerets).
152. "Ammonia Generation and NO_x Reduction in Dual-Layer Catalysts," ISCRE 22, Maastricht, The Netherlands, 9/12 (with Y. Liu and D. Luss).
153. "Kinetic and Reactor Modeling of the NH₃-SCR Converter: Fe- and Cu-Exchanged Zeolites as Single or Dual Layers," AIChE Annual Meeting, Pittsburgh, 10/12 (with P. Metkar, B. Shakya, and V. Balakotaiah).
154. "Modeling and Simulation of Dual-Layer NO_x Storage and Reduction (NSR) and Selective Catalytic Reduction (SCR) Monolithic Catalyst," AIChE Annual Meeting, Pittsburgh, 10/12 (with B. Shakya, presenter, and V. Balakotaiah).
155. "Spatiotemporal Behavior of Multifunctional Pt/Pd/Zeolite-Beta Diesel Oxidation Catalysts for Low-Temperature Oxidation of Hydrocarbons," AIChE Annual Meeting, Pittsburgh, 10/12 (with G. Bugosh, presenter, and R. Muncrief).
156. "Spatiotemporal Studies of NH₃ Formation Over Pt-Rh/BaO/Al₂O₃ LNT Monolith in the Presence of Excess CO₂ and H₂O," AIChE Annual Meeting, Pittsburgh, 10/12 (with P. Dasari, presenter, and R. Muncrief).
157. "Mechanistic Studies of Selective Catalytic Reduction of NO_x with C₃H₆ on Cu based Zeolite Monolith Catalyst," AIChE Annual Meeting, Pittsburgh, 10/12 (with R. Raj, presenter, and V. Balakotaiah).
158. "Ammonia Oxidation in Bi-functional Catalyst Consisting of Pt/Al₂O₃ and Cu Exchanged Zeolite Catalyst," AIChE Annual Meeting, Pittsburgh, 10/12 (with S. Shrestha).
159. "Lean NO_x Reduction with H₂ and CO Over Dual-Layer LNT-SCR Monolithic Catalysts," NASCRE 3, Houston, 3/13 (with Y. Zheng, presenter, and D. Luss).
160. "Cyclic Lean Reduction of NO by CO in Excess H₂O on Pt-Rh/Ba/Al₂O₃: Elucidating Mechanistic Features and Catalyst Performance," NASCRE 3, Houston, 3/13 (with P. Dasari, poster presenter).
161. "Modeling and Simulation of Layered Lean NO_x Trap and Selective Catalytic Reduction Monolithic Catalysts," NASCRE 3, Houston, 3/13 (with B. Shakya, presenter).
162. "New method for temperature measurements in honeycomb reactors," NASCRE 3, Houston, 3/13 (with H. Nguyen, presenter, and D. Luss).
163. "Fast Lean-Rich Cycling for enhanced lean NO_x conversion," NASCRE 3, Houston, 3/13 (with C. Perng, poster presenter).
164. "Mechanistic Studies of Selective Catalytic Reduction of NO_x with C₃H₆ on Cu based Zeolite Monolith Catalyst," NASCRE 3, Houston, 3/13 (with R. Raj, presenter, and V. Balakotaiah).
165. "Modeling and Simulation of Layered Lean NO_x Trap and Selective Catalytic Reduction Monolithic Catalysts," NAM, Louisville, KY 6/13 (with B. Shakya, presenter, and V. Balakotaiah).
166. "Spatiotemporal Studies of NH₃ Formation Over Pt-Rh/BaO/Al₂O₃ LNT Monolith in the Presence of

- Excess CO₂ and H₂O,” Louisville, KY 6/13 (poster; with P. Dasari, presenter).
167. “Ammonia Oxidation on Multi-functional Catalysts Consisting of Pt/Al₂O₃ and Fe Exchanged Zeolite,” North American Catalysis Society Conference, Louisville, KY 6/13 (with S. Shrestha).
 168. “Modeling and Optimization of Coupled Fe- and Cu- Based Selective Catalytic Reduction Monolithic “Ammonia Oxidation on Multi-functional Catalysts Consisting of Pt/Al₂O₃ and Fe Exchanged Zeolite,” Louisville, KY 6/13 (poster; with S. Shrestha, presenter).
 169. Catalyst,” AIChE Annual Meeting, San Francisco, November 2013 (with B. Shakya, presenter, and V. Balakotaiah).
 170. “Modeling and Analysis of Coupled NO_x Storage and Reduction and Selective Catalytic Reduction Monolithic Catalysts,” AIChE Annual Meeting, San Francisco, November, 2013 (with B. Shakya, presenter, and V. Balakotaiah).
 171. “Detailed Kinetic Modeling of Selective Catalytic Reduction of NO With C₃H₆ On Cu-Chabazite Monolithic Catalyst,” AIChE Annual Meeting, San Francisco, November 2013 (with R. Raj, presenter, and V. Balakotaiah).
 172. “In-situ DRIFTS Studies of Selective Catalytic Reduction of NO with C₃H₆ on Cu-chabazite Catalyst” AIChE Annual Meeting, San Francisco, November 2013 (with R. Raj, presenter, and V. Balakotaiah).
 173. “Spatiotemporal Studies of Methane Conversion on Pt/Pd Catalytic Monoliths,” AIChE Annual Meeting, San Francisco, November 2013 (with G. Bugosh, and V. Easterling).
 174. “Lean NO_x Reduction Over LNT-SCR Dual-Layer Catalyst: Impact of SCR Layer,” AIChE Annual Meeting, San Francisco, November 2013 (with Y. Zheng, and D. Luss, presenter).
 175. “Spatio-Temporal Concentration and Temperature Profiles During Periodic Hydrocarbon Oxidation in a Catalytic Monolith,” AIChE Annual Meeting, San Francisco, November 2013 (with H. Nguyen, presenter, and D. Luss, presenter).
 176. “Ammonia Oxidation on a Bi-Functional Pt/Al₂O₃ and Fe-Exchanged ZSM-5 Washcoated Monolith Catalyst,” AIChE Annual Meeting, San Francisco, November 2013 (with S. Shrestha, presenter, K. Kamasamudram, and A. Yezerets).
 177. “Lean NO_x Reduction with H₂ and CO Over Dual-Layer LNT-SCR Monolithic Catalysts,” AIChE Annual Meeting, San Francisco, November 2013 (with Y. Zheng, presenter, and D. Luss).
 178. “Fast Lean-Rich Cycling for Enhanced NO_x Conversion,” AIChE Annual Meeting, San Francisco, November 2013 (with C. Perng, and V. Easterling).
 179. “NO_x Reduction in Fast Cycling NO_x Storage and Reduction,” CLEERS, Dearborn, MI, 4/14 (with C. Perng and V. Easterling).
 180. “Experimental and Modeling Study of Selective Ammonia Oxidation on Multi-Functional Washcoated Monolith Catalysts,” ISCRE-23, Bangkok, Thailand, September 2014 (with S. Shrestha and K. Kamasamudram).
 181. “Simulations and Optimization of Combined Fe- and Cu-Zeolite SCR Monolith Catalysts,” ISCRE-23, Bangkok, Thailand, September 2014 (with B. Shakya and V. Balakotaiah).
 182. “Experimental and Simulation Study of Selective Ammonia Oxidation on Multi-Functional Washcoated Monolith Catalysts,” AIChE Annual Meeting, Atlanta, November 2014 (with S. Shrestha, presenter, K. Kamasamudram).
 183. “Impacts of CO, H₂ and C₃H₆ on the SCR Reactions Over a Cu-Chabazite SCR Catalyst,” AIChE Annual Meeting, Atlanta, November 2014 (with Y. Zheng, presenter, and D. Luss).
 184. “Steady-state and Dynamic Hysteresis Effects during Co-oxidation of CO and C₃H₆ over Pt/Al₂O₃ Diesel Oxidation Monolithic Catalyst,” AIChE Annual Meeting, Atlanta, November 2014 (with R. Raj and V. Balakotaiah, presenter).
 185. “Impact of Probe Intubation on Intra-channel Concentration Measurements by Spatially-resolved Mass Spectrometry,” AIChE Annual Meeting, Atlanta, November 2014 (with H. Nguyen, presenter, and D. Luss).
 186. “Reaction Studies on Na₂WO₄-Mn/SiO₂ Catalyst for Oxidative Coupling of Methane “ AIChE Annual Meeting, Atlanta, November 2014 (with Aseem, presenter, M. Conato, and J. Rimer).

187. "Spatio-temporal Features of NO_x reduction on LNT+SCR System: Effect of Hydrocarbon Reductant and Space Velocity," AIChE Annual Meeting, Atlanta, November 2014 (with K. Li, presenter, and V. Easterling).
188. "Fast Cycling NSR + SCR Over Dual-Layer Catalysts," CLEERS, Dearborn, MI, 4/15 (with Y. Zheng, M. Li, and D. Luss).
189. "A Study on Spatiotemporal Temperature and Concentration Measurement in Monolith Reactor," North American Catalysis Society Conference, Pittsburgh, PA, 6/15 (with D. Luss and H. Nguyen).
190. "Enhanced Low-temperature NO_x Conversion by High-Frequency Hydrocarbon Pulsing on a Dual Layer LNT-SCR Catalyst," North American Catalysis Society Conference, Pittsburgh, PA, 6/15 (with D. Luss and Y. Zheng, presenter).
191. "Spatio-temporal Features of Lean NO_x Reduction in NSR+SCR Sequential Configuration," North American Catalysis Society Conference, Pittsburgh, PA, 6/15 (poster; with V. Easterling and M. Li, presenter).
192. "Co-oxidation of CO and Hydrocarbons on Pd/Ceria-Zirconia/Al₂O₃," North American Catalysis Society Conference, Pittsburgh, PA, 6/15 (poster; with P. Laing and W. Lang, presenter).
193. "Selective Ammonia Oxidation on Multi-Layer Cu-SSZ-13/Pt/Al₂O₃ Monoliths," North American Catalysis Society Conference, Pittsburgh, PA, 6/15 (poster; with K. Kamasamudram, L. Olsson, and S. Shrestha, presenter).
194. "Oxidative Coupling of Methane (OCM) on Na₂WO₄-Mn/SiO₂: Impact of Reactor Type," AIChE Annual Meeting, Salt Lake City, UT, November 2015. (Aseem, presenter)
195. "Co-oxidation of CO and Hydrocarbons on Pd/Ceria-Zirconia/Al₂O₃ Three-Way Catalysts," AIChE Annual Meeting, Salt Lake City, UT, November 2015. (W. Lang, presenter, P. Laing, C. Hubbard, M. Sharma).
196. "Spatio-temporal Features of Lean NO_x Reduction in the NSR + SCR Sequential Configuration," AIChE Annual Meeting, Salt Lake City, UT, November 2015. (M. Li, presenter, V. Easterling).
197. "A Study on Spatiotemporal Temperature and Concentration Measurement in Monolith Reactor: On the Validity of Concentration Measurements by Spaci-MS," AIChE Annual Meeting, Salt Lake City, UT, November 2015. (with H. Nguyen, D. Luss).
198. "Spatially Resolved in Situ Study of Lean NO_x Reduction in the NSR+SCR Sequential Configuration," AIChE Annual Meeting, Salt Lake City, UT, November 2015. (poster; M. Li, presenter, V. Easterling).
199. "Co-Oxidation of CO and Hydrocarbons on Pd/Ceria-Zirconia/Al₂O₃ Three-Way Catalysts: Experiments and Modeling," ISCRE-24, Minneapolis, MN, June 2016 (with Wendy Lang, presenter, and Yisun Cheng, Carolyn Hubbard, Manish Sharma, and Paul Laing).
200. "Fast Cycling Storage and Reduction of NO: Experiments and Modeling," ISCRE-24, Minneapolis, MN, June, 2016 (with Allen Ting, Mengmeng Li, Yang Zheng, Vemuri Balakotaiah, and Dann Luss).
201. "Co-Oxidation of CO and Hydrocarbons on Pd/Ceria-Zirconia/Al₂O₃ Three-Way Catalysts: Experiments and Modeling," AIChE Annual Meeting, San Francisco, CA, November 2016. (W. Lang, presenter, P. Laing, C. Hubbard, M. Sharma).
202. "Lean-Rich Switching Over a Modified Three-Way Catalyst: Experiments and Modeling," AIChE Annual Meeting, San Francisco, CA, November 2016. (M. Li, presenter, S. Malamis, and W. S. Epling).
203. "Spatial and Temporal Features of the Catalyzed Hydrocarbon Trap," AIChE Annual Meeting, San Francisco, CA, November 2016. (P.Y. Peng, presenter, and D. Luss).
204. "Spatial and Temporal Features of the Catalyzed Hydrocarbon Trap," North American Catalysis Society Conference, Denver, CO 6/17 (with D. Luss and P.-Y. Po, presenter).
205. "Co-Oxidation of CO and Hydrocarbons on Pd/Ceria-Zirconia/Al₂O₃ Three-Way Catalysts: Experiments and Modeling," North American Catalysis Society Conference, Denver, CO 6/17 (with Y. Cheng, C. Hubbard, P. Laing, and W. Lang, presenter).
206. "Effect of Fast Cycling on the Formation of HC Intermediates and NO_x Conversion – Modeling and Experiment," North American Catalysis Society Conference, Denver, CO 6/17 (with V. Balakotaiah,

- and A. W.L. Ting, presenter).
207. "The Effects of Aging on Steady State Ammonia Oxidation over Pt/ γ -Al₂O₃," North American Catalysis Society Conference, Denver, CO 6/17 (with D. Wang, A. Kumar, and P. Singh Dhillon, presenter).
 208. "Lean-Rich Switching over a Modified Three-Way Catalyst: Experiments and Modeling," North American Catalysis Society Conference, Denver, CO 6/17 (with M. Li, S. Malamis, and B. Epling).
 209. "Spatio-Temporal Features of the Hydrocarbon Trap: Spatial Nonuniformities and Sustained Oscillations," CLEERS, Ann Arbor, MI, 10/17 (with P. Y. Peng and D. Luss).
 210. "Experimental and Modeling Studies of Cycle Frequency, Reductant Type and Non-Isothermal Effect on the Performance of a Lean NO_x Trap," CLEERS, Ann Arbor, MI, 10/17 (with W.L. Ting, presenter, and V. Balakotaiah).
 211. "CO, C₂H₂, and C₃H₆ Oxidation on Pd/Ceria-Zirconia/Al₂O₃ Three-Way Catalysts," AIChE Annual Meeting, Minneapolis, MN, October 2017 (W. Lang, presenter, P. Laing, C. Hubbard, M. Sharma).
 212. "Experimental and Modeling Studies of Cycle Frequency, Reductant Type and Non-isothermal Effect on the Performance of a Lean NO_x Trap," AIChE Annual Meeting, Minneapolis, MN, October 2017 (W.L. Ting, presenter, and V. Balakotaiah).
 213. "Fast Cycling to Achieve High NO_x Conversion in Lean Exhaust: Role of Ceria," AIChE Annual Meeting, Minneapolis, MN, October 2017 (Z. Zhou, presenter, and D. Luss).
 214. "The Effects of Aging on Steady State Ammonia Oxidation over Pt/ γ -Al₂O₃," AIChE Annual Meeting, Minneapolis, MN, October 2017 (with P. Dhillon, presenter, A. Kumar, D. Wang, and S. Joshi).
 215. "Use of Sacrificial Agent to Enhance Gas Transport Through the Washcoat," AIChE Annual Meeting, Minneapolis, MN, October 2017 (with P. Dhillon, presenter, A. Kumar, D. Wang, and S. Joshi).
 216. "Low Temperature NO and Hydrocarbon Trapping over Pd-exchanged Zeolite Passive NO_x Adsorbers," AIChE Annual Meeting, Minneapolis, MN, October 2017 (with S. Malamis, presenter, W. Epling).
 217. "NO Uptake and Desorption on Fe-Modified Pd/ZSM-5: Impact of Pd and Fe Loading," AIChE Annual Meeting, Minneapolis, MN, October 2017 (with K. Karinshak and W. Epling).
 218. "Fast NO_x Storage and Reduction (NSR): Experiments and Modeling," CLEERS, Ann Arbor, MI, 9/18 (with A. Ting, Z. Zhou, D. Luss, and V. Balakotaiah).
 219. "Modeling Studies of Cycle Frequency, Reductant Type and Non-isothermal Effect on the Performance of a Lean NO_x Trap," AIChE Annual Meeting, Pittsburgh, PA, October 2018 (with W.L. Ting and V. Balakotaiah).
 220. "Experimental and Modeling Studies of Passive NO_x Adsorbers: Pd/H-ZSM5," AIChE Annual Meeting, Pittsburgh, PA, October 2018 (with M. Ambast, presenter, K. Karinshak and W. Epling).
 221. "Low Temperature NO and Hydrocarbon Trapping over Pd-exchanged Zeolite Passive NO_x Adsorbers," AIChE Annual Meeting, Pittsburgh, PA, October 2018 (with S. Malamis, presenter, W. Epling).
 222. "Fast Cycling to Achieve High NO_x Conversion in Lean Exhaust: Role of Ceria," AIChE Annual Meeting, Pittsburgh, PA, October 2018 (Z. Zhou, presenter, and D. Luss).
 223. "Experiments and Modeling for Enhanced Transport in SCR and Ammonia Slip Catalysts," AIChE Annual Meeting, Pittsburgh, PA, October 2018 (with P. Dhillon, presenter, A. Kumar, D. Wang, and S. Joshi).
 224. "Oscillations and Hysteresis during Hydrocarbon Oxidation on a Diesel Oxidation Catalyst," AIChE Annual Meeting, Pittsburgh, PA, October 2018 (P.Y. Peng, presenter, and D. Luss).
 225. "Nature of Active Sites in 1% Pd/SSZ-13 for Passive NO_x Adsorption (PNA)," North American Symposium of Chemical Reaction Engineering, Houston, TX, March 2019 (with U. Menon, presenter, Bhuiyan Md. Mushfikur Rahman, A. Gupta, T. Salavati-Fard, H. Thirumalai, M. Ambast, L. Grabow).
 226. "Modeling and optimization of the combined NO_x and Hydrocarbon Trap," North American Meeting of the Catalysis Society, Chicago, IL, June 2019 (with S. Malamis, presenter).
 227. "Optimizing the Dual-Layer Pt/Al₂O₃ + Cu/SSZ-13 Washcoated Monolith: Selective Oxidation of NH₃ to N₂," North American Meeting of the Catalysis Society, Chicago, IL, June 2019 (with P. Singh

- Dhillon, presenter, D. Wang, A. Kumar, S. Joshi).
228. "Maximizing Low Temperature NO_x Uptake on Pd/CHA: Impact of Operating Conditions and Trap Composition," North American Meeting of the Catalysis Society, Chicago, IL, June 2019 (with A. Gupta, S. Kang, M. Ambast).
 229. "Enhanced Conversion of Methane and NO_x From Natural Gas Vehicle Exhaust: PGM + Mn_{0.5}Fe_{2.5}O₂ spinel," North American Meeting of the Catalysis Society, Chicago, IL, June 2019 (with S. Kang, presenter, K. Karinshak, S. Golden).
 230. "Enhanced NO_x Conversion with PGM/Spinel: Impact of Feed Modulation and Catalyst Architecture," North American Meeting of the Catalysis Society, Chicago, IL, June 2019 (with Z. Zhou, presenter, D. Luss).
 231. "Nature of Active Sites in 1% Pd/SSZ-13 for Passive NO_x Adsorption (PNA)," North American Meeting of the Catalysis Society, Chicago, IL, June 2019 (with U. Menon, presenter, Bhuiyan Md. Mushfikur Rahman, A. Gupta, T. Salavati-Fard, H. Thirumalai, M. Ambast, L. Grabow).
 232. "Maximizing Low Temperature NO_x Uptake on Pd/CHA: Impact of Operating Conditions and Trap Composition," AIChE Annual Meeting, Orlando, FL, November 2019 (with A. Gupta, presenter).
 233. "Coupled Trapping and Reaction for Emission Control of Diesel and Natural Gas Fueled Vehicles," AIChE Annual Meeting, Orlando, FL, November 2019.
 234. "Experimental And Modeling Studies of Passive NO_x Adsorbers: Pd/H-ZSM-5 And Pd/SSZ-13," AIChE Annual Meeting, Orlando, FL, November 2019 (with M. Ambast, presenter).
 235. "Enhanced NO, CO and C₃H₆ Conversion on Precious Group Metal Catalysts: Impact of Oxygen Storage Material and Catalyst Architecture," AIChE Annual Meeting, Orlando, FL, November 2019 (with Z. Zhou, D. Luss).
 236. "Sustained Oscillations Caused by Feed Modulation During Methane Oxidation on Four-Way Catalysts," AIChE Annual Meeting, Orlando, FL, November 2019 (with K. Karinshak, presenter, S. Kang, S. Golden).
 237. "Multi-Functional Catalytic System for NO_x Trapping and Hydrocarbon Oxidation from Diesel and Advanced Combustion Engines: Impact of Operating Conditions & Trap Composition," AIChE Annual Meeting, Orlando, FL, November 2019 (Bhuiyan Md. Mushfikur Rahman, presenter, U. Menon, A. Gupta, S. Kang, L. Grabow).
 238. "Activity Enhancement and Microkinetics of NH₃ Oxidation on Pt/Al₂O₃: Apparent Rate Enhancement by Ball Milling and Structure Sensitivity Effects," AIChE Annual Meeting, Virtual, November 2020 (with R. Ghosh, presenter, D. Wang).
 239. "Coupled NO and Hydrocarbon Trapping, Release and Conversion on Pd/SSZ-13 and Pt-Pd/BEA," AIChE Annual Meeting, Virtual, November 2020 (with A. Gupta, presenter).
 240. "Modeling Studies of Trapping and Conversion of NO_x and Hydrocarbons in a Structured Catalytic Reactor: Pd/SSZ-13 and Pd/Pt/BEA," AIChE Annual Meeting, Virtual, November 2020 (with M. Ambast, presenter, A. Gupta).
 241. "Optimization and Modelling of Methane Oxidation on Four-Way Catalysts," AIChE Annual Meeting, Virtual, November 2020 (with K. Karinshak, presenter, P.W. Chen).
 242. "Enhanced CH₄ Conversion over Pt+Pd/Al₂O₃ + Mn_{0.5}Fe_{2.5}O₄ Spinel catalyst: Impact of Oxygen Storage Material," AIChE Annual Meeting, Virtual, November 2020 (with P.W. Chen, presenter, D. Maiti, L. Grabow).
 243. "Rational Design of PGM-spinel oxide catalysts for enhanced methane conversions," ACS Fall Meeting, Virtual, August 2021 (with D. Maiti, presenter, P.W. Chen, Kyle Karinshak, K. Rao, R.-F. Liu, L. Grabow).
 244. "CH₄ steam reforming on Pt+Pd/Al₂O₃ monolith catalyst: impact of Mn_{0.5}Fe_{2.5}O₄ spinel addition," ACS Fall Meeting, Virtual, August 2021 (with P.W. Chen, presenter, D. Maiti, L. Grabow).
 245. "CH₄ Oxidation over a Pt-Pd/Al₂O₃ Monolith Catalyst: Experiments and Modeling," AIChE Annual Meeting, November 2021 (with Kyle Karinshak, Pak Wing Chen, Austin Morales).
 246. "CH₄ Steam Reforming on Pt+Pd/Al₂O₃ Monolith Catalyst: Impact of Mn_{0.5}Fe_{2.5}O₄ Spinel Addition,"

- AICHE Annual Meeting, November 2021 (with Pak Wing Chen, presenter, D. Maiti, R.F. Liu, L. Grabow).
247. "Effects of $C_{12}H_{26}$ on NO Uptake on Pd/SSZ-13: Experiments and Modeling," AIChE Annual Meeting, November 2021 (with M. Ambast, A. Gupta).
 248. "Spatiotemporal Features of NO_x + Hydrocarbon Trapping and Conversion in a Sequential Monolith Configuration," North American Meeting of the Catalysis Society, New York, NY, June 2022 (with A. Gupta, speaker).
 249. "CH₄ Conversion by Steam Reforming during Oxidation over Pt + Pd/Al₂O₃ Monolith Catalysts: Kinetic Model Development," North American Meeting of the Catalysis Society, New York, NY, June 2022 (with P.W. Chen, speaker, R.F. Liu, D. Maiti, L. Grabow).
 250. "Spatiotemporal Features of NO_x + Hydrocarbon Trapping and Conversion in a Sequential Monolith Configuration," North American Meeting of the Catalysis Society, New York, NY, June 2022 (with A. Gupta, speaker).
 251. "Spatio-Temporal Features of Coupled Oxidation and Reforming of Methane on Pt+Pd/Al₂O₃ Monolith Catalyst," North American Meeting of the Catalysis Society, New York, NY, June 2022 (with J. Ratcliff, K. Karinshak).
 252. "Single Atom Alloys 2.0: Exploiting Undercoordination for Stronger Dissociative CH₄ Chemisorption," North American Meeting of the Catalysis Society, New York, NY, June 2022 (with D. Maiti, speaker, L. Grabow).
 253. "Enhanced CH₄ Conversion Using Dual Layer Pt-Pd/Spinel Oxide Catalysts," North American Meeting of the Catalysis Society, New York, NY, June 2022 (with D. Maiti, speaker, P.W. Chen, R.F. Liu, L. Grabow).
 254. "Impact of Feed Composition on the Spatial Features of Coupled Methane Oxidation and Reforming," AIChE Annual Meeting, November 2022 (with Jonathan Ratcliff, speaker, Kyle Karinshak, Pak Wing Chen).
 255. "CH₄ Conversion by Steam Reforming During Oxidation over Pt + Pd/Al₂O₃ Monolith Catalysts: Kinetic Model Development," AIChE Annual Meeting, November 2022 (with Pak Wing Chen, speaker, K. Karinshak, D. Maiti, R.F. Liu, L. Grabow).
 256. "Pi-Criterion Analysis of Non-Steady State Catalytic Oxidation Reactions," AIChE Annual Meeting, November 2022 (with A. Morales, speaker, P. Bollini).
 257. "Reductant Induced Redox Behavior of Atomically-Dispersed Palladium in Pd-CHA," AIChE Annual Meeting, November 2022 (with S.P. Solanki, speaker, M. Ambast, C. Paolucci, L. Grabow).
 258. "Forced Dynamic Operation for Enhanced Performance:
 259. Propene Conversion to Acrolein and Acrylonitrile," ISCRE 27, June 2023 (with M. Moniruzzaman, L. Grabow, Z. Guo, W. Epling).
 260. "Dynamic Operation of Chemical Reactors: Classifying Kinetics for Quasi Steady State Enhancement," ISCRE 27, June 2023 (poster; with A. Morales, presenter; P. Bollini).
 261. "Steady State Multiplicity Features and Spatial Inhomogeneities During Methane Oxidation on Pt-Pd/Al₂O₃ Monolith Catalyst," ISCRE 27, June 2023 (poster; with J. Ratcliff).
 262. "Impact of Feed Temperature and Composition on the Steady State Performance and Spatial Features of Catalytic Oxidation of Methane," North American Meeting of the Catalysis Society, Providence, RI, June 2023 (with J. Ratcliff, speaker).
 263. "Relating Kinetic and Mechanistic Features to Dynamic Rate Enhancement in Catalytic Oxidation Reactions," North American Meeting of the Catalysis Society, Providence, RI, June 2023 (with A. Morales, speaker; P. Bollini).

Graduate Students and Post Docs Supervised

Current Research Group

<u>Student</u>	<u>Degree Date</u>
Chenhao Fang (PhD candidate)	2023
Pak Wing Chen (PhD candidate; with L. Grabow)	2023
Jonathan Ratcliff (PhD candidate)	2024
Mohammad Moniruzzaman (PhD candidate)	2025
Austin Morales (PhD candidate; with P. Bollini)	2025
Kai Wu (PhD candidate; with L. Grabow)	2026
Elmer Ledesma (PhD candidate)	2027
Prajyot Srivistava (PhD candidate)	2028

*Previous Research Group*Post Docs

Dr. Jun Choi, 2001-2003
 Dr. Rachel Muncrief, 2002 – 2007
 Dr. Vinay Medhekar, 2005 – 2006
 Dr. Hongmei An, 2007 – 2009
 Dr. Xiaolin Zheng, Jan. 2010 – Sept. 2010
 Dr. Alejandrina Campanella (PhD), Dec. 2009 – Sept. 2011
 Dr. Geoffrey Goldwin (PhD), Sept. 2010 – Sept. 2011
 Dr. Rebecca Fushimi (PhD), Dec. 2010 – Sept. 2011
 Dr. Munish Sharma (with B. Epling), June 2013 – Aug. 2014
 Dr. Hoseok (Will) Song, August 2012 – December 2014
 Dr. Ali Gardezi, June 2014 – August 2015
 Dr. Vence Easterling, June 2013 – March 2016
 Dr. Sungbong Kang, Nov. 2017 – Dec. 2019
 Dr. Unmesh Menon, November 2015 – 2018
 Dr. Gregory Bugosh, January 2015 – 2020

Graduated Students (38 PhD, 12 MS)

<u>Student</u>	<u>Thesis Title</u>	<u>Completed</u>
Gregory Funk, Ph.D. (with K. Ng)	Effect of Wetting on Catalytic Gas-Liquid Reactions	10/89
Martha Garske, Ph.D.	Kinetics and Multiple Rate States of Platinum-Catalyzed Carbon Monoxide Oxidation	2/90
Philippe Cini, Ph.D.	Development of the Segregated Multiphase Flow Catalytic Tubular Reactor	5/90
Regan Seymour, M.S.	Progress in Binary Inorganic Membranes for Catalysis and Gas Separation	9/92
Paul Watson, Ph.D.	An Experimental and Modeling Study of Phase Transition and Exothermic Reaction in the Multiphase Catalytic Pellet	9/92
David Sullivan, Ph.D. (with W. Conner)	Surface Analysis with Infrared Emission Spectroscopy	5/94

Priya Kharbanda, M.S.	Vaporization in a Partially Wetted Catalytic Pellet: Linking Theory and Experiments	5/94
Chin Lee, M.S.	Development of Microporous Silica Membranes	5/95
Andrew Oliveiro, Ph.D. (with W. Conner)	Understanding the Interaction Between Platinum and Ceria in Pt/Ceria/Alumina Catalyzed Reactions	8/95
Balamurali Krishna Nair, M.S.	Analysis and Design of a Palladium Membrane Fuel Processor	8/03
Madhu Bhattacharya, Ph.D. (with V. Balakotaiah)	Low Dimensional Models of Chemical Reactors	8/04
Pranav Khanna, M.S.	Kinetics Studies of NO _x Storage and Reduction	12/04
Karen Kabin, PhD	NO _x Storage and Reduction Studies on Pt/Ba/Alumina Monolithic Catalysts	1/05
Manish Sharma, PhD (with V. Balakotaiah)	Modeling and Simulation of Periodic Storage and Reaction in NO _x Traps	12/05
James R. Lattner, PhD	Autothermal Reforming (ATR) and ATR Membrane Reactors for Hydrogen Production: Experiments and Modeling	12/05
Balamurali Krishna Nair, PhD	Synthesis and Characterization of Pd-Based Hollow Fiber Membranes for Reaction and Separation	11/06
Robert Clayton, PhD (with V. Balakotaiah)	Steady-State and Cyclic Studies of Pt/BaO/Al ₂ O ₃ Lean NO _x Traps	11/08
Shih-Chin Hsu, MS	Optimization of Palladium Nanopore Membrane Synthesis	12/08
Jin Xu, PhD (with V. Balakotaiah)	Microkinetic Modeling of NO-H ₂ -O ₂ -NH ₃ System on Pt/BaO/Al ₂ O ₃ Monolith Catalysts	9/09
Nelson Salazar, MS	Selective Catalytic Reduction of NO _x on Fe/ZSM5 Zeolite Monolith Catalysts	10/09
Divesh Bhatia, PhD (with V. Balakotaiah)	Modeling of NO _x Storage and Reduction on Pt/BaO/Al ₂ O ₃ Monolith Catalysts	8/10
Saurabh Joshi, PhD (with V. Balakotaiah)	Experimental and Modeling Studies for Real Time Simulations of Catalytic Monolithic Reactors	8/10
Ashok Kumar, PhD (with V. Balakotaiah)	Mechanistic and Microkinetic Studies of NO _x Storage and Reduction (NSR) on Pt/BaO/Al ₂ O ₃ Catalysts Using Temporal Analysis of Products (TAP)	8/10
Sameer Israni, PhD	Hydrogen Generation and Purification in Pd-Based Membrane Reactors	9/10
Gregory Bugosh, MS (with R. Muncrief)	Combustion and Emissions Analysis of Alternative Diesel Fuels in a Compression Ignition Engine	8/10
Prasanna Dasari, MS	Studies of Steady-State Reactions of NO, CO	10/10

(with R. Muncrief)	and H ₂ O In Pt-Ba/Al ₂ O ₃ Lean NO _x Traps	
Yongjie Ren, MS	Effects of Rh, CeO ₂ and Regeneration Conditions on NSR Monolith Catalysts using H ₂ as the Reductant	6/11
Di Wang, MS (with J. Rimer)	Ammonia Uptake on Fe- and Cu-Exchanged Zeolites	10/11
Pranit Metkar, PhD (with V. Balakotaiah)	Selective Catalytic Reduction in Fe- and Cu-Exchanged Zeolites	6/12
Yi Liu, PhD (with D. Luss)	NO _x Removal by LNT-SCR Dual-Layer Catalysts	9/12
Ogochukwu Enekwizu, MS	Performance of a Composite Palladium Membrane Reactor for Dehydrogenation of Ethylbenzene to Styrene	5/13
Prasanna Dasari, PhD	Experimental Studies of NO _x Storage and Reduction on Lean NO _x Traps	8/13
Bijesh Shakya, PhD (with V. Balakotaiah)	Studies of Pt Dispersion and Catalyst Architecture for Lean NO _x Reduction	11/13
Charles Perng, MS	Fast Lean-Rich Cycling for Enhanced NO _x Conversion on Storage and Reduction Catalysts	3/14
Richa Raj, PhD (with V. Balakotaiah)	Kinetic and Mechanistic Studies of NO _x Reduction with Propylene over Cu-SSZ-13 and Co-oxidation of CO/C ₃ H ₆ over Diesel Oxidation Pt/Al ₂ O ₃ Catalyst	9/14
Gregory Bugosh, PhD	Performance Studies of Multifunctional Pt/Pd Monolithic Catalysts for Hydrocarbon Oxidation Emission Control	5/15
Sachi Shrestha, PhD	Understanding the Behavior of Bi-functional Catalyst in Selective Catalytic Oxidation of Ammonia to Nitrogen	8/15
Yang Zheng, PhD (with D. Luss)	Applied and Fundamental Studies of LNT-SCR Dual-layer Monolithic Catalysts for Lean NO _x Emission Control	9/15
Hoang Nguyen, PhD (with D. Luss)	Spatiotemporal Temperature and Concentration Measurements in a Monolith Reactor	10/15
Mengmeng Li, PhD	Spatio-temporal Features of Combined NO _x Storage and Reduction and Selective Catalytic Reduction	6/17
Aseem, PhD	Oxidative Coupling of Methane Over Mixed Metal Oxides: Thermokinetic and Oxygen Distribution Effects	9/17
Allen Wei-Lun Ting, PhD (with V. Balakotaiah)	Fast Cycling NO _x Storage and Reduction on Lean NO _x Trap Catalytic Reactor	5/18

Wendy Lang, PhD	CO and Hydrocarbon Oxidation on Pd/Ceria-Zirconia/Alumina Three-Way Catalysts	8/18
Po-Yu Peng, PhD (with D. Luss)	Selectivity and Spatiotemporal Features of Sorption and Oxidation in Monolith and Packed Bed Reactors	8/18
Sotirios Malamis, PhD	Characterization and Optimization of Multi-functional Automotive Catalysts	10/19
Pritpal Singh Dhillon, PhD	Reaction and Transport Coupling in Multi-Functional Catalysts for the Selective Oxidation of Ammonia to Nitrogen	12/19
Rajat Ghosh, PhD	Enhanced Selective Oxidation of NH ₃ in a Pt/Al ₂ O ₃ @Cu/ZSM-5 Core-Shell Catalyst	12/20
Zhiyu Zhou, PhD (with D. Luss)	Role of Storage Material in NO _x Storage and Reduction (NSR) and Three-Way Catalysts During Cycling Operation	12/20
Mugdha Ambast, PhD	Experimental and Modeling Studies of Passive NO _x Adsorbers	5/21
Karinshak, Kyle, PhD	Enhanced Methane Oxidation Catalysis Through Feed Modulation and Oxygen Storage	11/21
Gupta, Abhay, PhD	Analysis and Design of Structured Multi-functional Trapping Catalysts for Conversion of Hydrocarbons and NO _x from Diesel and Advanced Combustion Engines	8/22
Pak Wing Chen, PhD (with L. Grabow)	Enhanced Methane Conversion over Four-Way Catalyst for Stoichiometric Natural Gas Vehicle Emission Control	6/23
Chenhao Fang, PhD	Sulfur Poisoning and Regeneration of Pt/Al ₂ O ₃ Catalysts in Emission Control	8/23

Graduate Students Advised as Industrial Collaborator & Committee Member

Zeru Tekie, Ph.D. (with B. Morsi, U. Pittsburgh)	Mass Transfer and Modeling of Liquid-Phase Cyclohexane Oxidation Process in Agitated Reactors	1/97
I-Ming Hsing, Ph.D. (with K. Jensen, MIT)	Simulations of Micromachined Chemical Reactors	9/97
Ravi Srinivasan, Ph.D. (with K. Jensen, MIT)	Surface-Catalyzed Oxidation in Micromachined Chemical Reactors	12/97

Madhav Acharya, Ph.D. Synthesis and Applications of Supported Carbon
(with H. Foley, U. Delaware) Membranes

12/98