



The Changing Landscape of Hydrocarbon Feedstocks for Chemical Production: Implications for Catalysis: Proceedings of a Workshop

DETAILS

130 pages | 6 x 9 | PAPERBACK

ISBN 978-0-309-44479-8 | DOI: 10.17226/23555

AUTHORS

Joe Alper, Rapporteur; Board on Chemical Sciences and Technology; Division on Earth and Life Studies; National Academies of Sciences, Engineering, and Medicine

[BUY THIS BOOK](#)

[FIND RELATED TITLES](#)

Visit the National Academies Press at NAP.edu and login or register to get:

- Access to free PDF downloads of thousands of scientific reports
- 10% off the price of print titles
- Email or social media notifications of new titles related to your interests
- Special offers and discounts



References

- Alcaide, F., P.-L. Cabot, and E. Brillás. 2006. Fuel cells for chemicals and energy cogeneration. *Journal of Power Sources* 153(1):47-60.
- Almutairi, S. M. T., B. Mezari, P. C. M. M. Magusin, E. A. Pidko, and E. J. M. Hensen. 2012. Structure and reactivity of Zn-modified ZSM-5 zeolites: The importance of clustered cationic Zn complexes. *ACS Catalysis* 2(1):71-83.
- Alvarez-Galvan, M. C., N. Mota, M. Ojeda, S. Rojas, R. M. Navarro, and J. L. G. Fierro. 2011. Direct methane conversion routes to chemicals and fuels. *Catalysis Today* 171(1):15-23.
- American Chemistry Council. 2013a. *Shale gas, competitiveness, and new US chemical industry investment: An analysis based on announced projects*. Washington, DC: American Chemistry Council.
- . 2013b. Year-end 2013 chemical industry situation and outlook: American chemistry is back in the game. Washington, DC: American Chemistry Council.
- . 2014. American chemistry: Growing the U.S. economy, providing jobs, enhancing safety. Washington, DC: American Chemistry Council. Available at <https://blog.americanchemistry.com/2014/06/american-chemistry-growing-the-u-s-economy-providing-jobs-enhancing-safety> [accessed March 7, 2016].
- . 2015a. The rising competitive advantage of U.S. plastics. Washington, DC: American Chemistry Council.
- . 2015b. Guide to the business of chemistry—2015. Washington, DC: American Chemistry Council.
- . 2016. Shale gas and new U.S. Chemical industry investment: \$164 billion and counting. Washington, DC: American Chemistry Council. Available at <https://www.americanchemistry.com/Policy/Energy/Shale-Gas/Slides-Shale-Gas-and-New-US-Chemical-Industry-Investment.pdf> [accessed March 7, 2016].
- ARPA-E (Advanced Research Projects Agency-Energy). 2012. *Efficient natural gas-to-methanol conversion*. Available at <http://arpa-e.energy.gov/?q=slick-sheet-project/efficient-natural-gas-methanol-conversion> [accessed April 13, 2016].
- Ascoop, I., V. V. Galvita, K. Alexopoulos, M.-F. Reyniers, P. Van Der Voort, V. Bliznuk, and G. B. Marin. 2016. The role of CO₂ in the dehydrogenation of propane over WO_x-VO_x/SiO₂. *Journal of Catalysis* 335:1-10.
- Au, C.-T., T.-J. Jhou, W.-J. Lai, and C.-F. Ng. 1997. An ab initio study of methane activation on lanthanide oxide. *Catalysis Letters* 49(1-2):53-58.
- Banerjee, R., Y. Proshlyakov, J. D. Lipscomb, and D. A. Proshlyakov. 2015. Structure of the key species in the enzymatic oxidation of methane to methanol. *Nature* 518(7539):431-434.
- Basset, J.M., C. Coperet, D. Soulivong, M.Taoufik, J. Thivolle Cazat. 2010. Metathesis of Alkanes and Related Reactions, *Accounts of Chemical Research* 43: 323-334.

- Beck, B., V. Fleischer, S. Arndt, M. G. Hevia, A. Urakawa, P. Hugo, and R. Schomäcker. 2014. Oxidative coupling of methane—A complex surface/gas phase mechanism with strong impact on the reaction engineering. *Catalysis Today* 228:212-218.
- Bell, A. 2016. “Conversion of Methane and Light Alkanes to Chemicals over Heterogeneous Catalysts-Lessons Learned from Experiment and Theory.” Presented at the Board on Chemical Sciences and Technology Workshop on The Changing Landscape of Hydrocarbon Feedstocks for Chemical Production: Implications for Catalysis, Washington, DC, March 7-9, 2016.
- Bodke, A. S., D. A. Olschki, L. D. Schmidt, and E. Ranzi. 1999. High selectivities to ethylene by partial oxidation of ethane. *Science* 285(5428):712-715.
- Botella, P., E. García-González, A. Dejoz, J. M. López Nieto, M. I. Vázquez, and J. González-Calbet. 2004. Selective oxidative dehydrogenation of ethane on movtenbo mixed metal oxide catalysts. *Journal of Catalysis* 225(2):428-438.
- Bricker, J. 2016. “History and State of the Art of Ethane/Propane Dehydrogenation Catalysis.” Presented at the Board on Chemical Sciences and Technology Workshop on The Changing Landscape of Hydrocarbon Feedstocks for Chemical Production: Implications for Catalysis, Washington, DC, March 7-9, 2016.
- Brookhart, M., M. Findlater, D. Guironnet, and T. W. Lyons. 2012. Synthesis of para-xylene and toluene. Filed and issued.
- Brown, M. J., and N. D. Parkyns. 1991. Progress in the partial oxidation of methane to methanol and formaldehyde. *Catalysis Today* 8(3):305-335.
- Cavani, F., N. Ballarini, and A. Cericola. 2007. Oxidative dehydrogenation of ethane and propane: How far from commercial implementation? *Catalysis Today* 127(1-4):113-131.
- Chan, S. I., and S. S. F. Yu. 2008. Controlled oxidation of hydrocarbons by the membrane-bound methane monooxygenase: The case for a tricopper cluster. *Accounts of Chemical Research* 41(8):969-979.
- Chin, Y.-H., C. Buda, M. Neurock, and E. Iglesia. 2013. Consequences of metal–oxide interconversion for C–H bond activation during CH₄ reactions on Pd catalysts. *Journal of the American Chemical Society* 135(41):15425-15442.
- Cornils, B., W. A. Herrmann, and M. Rasch. 1994. Otto Roelen, pioneer in industrial homogeneous catalysis. *Angewandte Chemie International Edition in English* 33(21):2144-2163.
- Cui, Y., X. Shao, M. Baldofski, J. Sauer, N. Nilius, and H. J. Freund. 2013. Adsorption, activation, and dissociation of oxygen on doped oxides. *Angewandte Chemie, International Edition in English* 52(43):11385-11387.
- Czuprat, O., S. Werth, S. Schirrmeister, T. Schiestel, and J. Caro. 2009. Olefin production by a multistep oxidative dehydrogenation in a perovskite hollow-fiber membrane reactor. *ChemCatChem* 1(3):401-405.
- DeRosa, S. E., and D. T. Allen. 2015. Impact of natural gas and natural gas liquids supplies on the United States chemical manufacturing industry: Production cost effects and identification of bottleneck intermediates. *ACS Sustainable Chemistry & Engineering* 3(3):451-459.
- Dubois, J.-L., M. Bisiaux, H. Mimoun, and C. J. Cameron. 1990. X-ray photoelectron spectroscopic studies of lanthanum oxide based oxidative coupling of methane catalysts. *Chemistry Letters* 19(6):967-970.

- Duff, B. 2012. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy presentation at the National Academies of Sciences, Engineering, and Medicine's Board on Chemical Sciences and Technology's Chemical Sciences Roundtable Workshop, May 31, 2012.
- EIA (U.S. Energy Information Administration). 2015. U.S. Crude Oil and Natural Gas Proved Reserves. Available at <https://www.eia.gov/naturalgas/crudeoilreserves> [accessed March 7, 2016].
- . 2016. *Short-term outlook for hydrocarbon gas liquids*. Washington, DC: U.S. Department of Energy.
- EPA (U.S. Environmental Protection Agency). 2010. *Methane and nitrous oxide emissions from natural sources*. Available at <https://www3.epa.gov/climatechange/ghgemissions/gases/ch4.html> [accessed May 31, 2016].
- Fan, Q. 2015. Non-Faradaic electrochemical promotion of catalytic methane reforming for methanol production. Filed and issued.
- Fang, X., S. Li, J. Gu, and D. Yang. 1992. Preparation and characterization of W-Mn catalyst for oxidative coupling of methane. *Journal of Molecular Catalysis (China)* 6:255-261.
- Feng, X., J. Wu, A. T. Bell, and M. Salmeron. 2015. An atomic-scale view of the nucleation and growth of graphene islands on Pt surfaces. *The Journal of Physical Chemistry C* 119(13):7124-7129.
- Ferreira, V. J., P. Tavares, J. L. Figueiredo, and J. L. Faria. 2013. Ce-doped La₂O₃-based catalyst for the oxidative coupling of methane. *Catalysis Communications* 42:50-53.
- Forde, M. M., R. D. Armstrong, C. Hammond, Q. He, R. L. Jenkins, S. A. Kondrat, N. Dimitratos, J. A. Lopez-Sanchez, S. H. Taylor, D. Willock, C. J. Kiely, and G. J. Hutchings. 2013. Partial Oxidation of Ethane to Oxygenates Using Fe- and Cu-Containing ZSM-5. *Journal of the American Chemical Society* 135(30):11087-11099.
- Galvita, V., G. Siddiqi, P. Sun, and A. T. Bell. 2010. Ethane dehydrogenation on Pt/Mg(Al)O and PtSn/Mg(Al)O catalysts. *Journal of Catalysis* 271(2):209-219.
- Gao, J., Y. Zheng, G. B. Fitzgerald, J. de Joannis, Y. Tang, I. E. Wachs, and S. G. Podkolzin. 2014. Structure of Mo₂C_x and Mo₄C_x molybdenum carbide nanoparticles and their anchoring sites on ZSM-5 zeolites. *The Journal of Physical Chemistry C* 118(9):4670-4679.
- Gao, J., Y. Zheng, J. M. Jehng, Y. Tang, I. E. Wachs, and S. G. Podkolzin. 2015. Catalysis. Identification of molybdenum oxide nanostructures on zeolites for natural gas conversion. *Science* 348(6235):686-690.
- Gärtner, C. A., A. C. van Veen, and J. A. Lercher. 2013. Oxidative dehydrogenation of ethane: Common principles and mechanistic aspects. *ChemCatChem* 5(11):3196-3217.
- . 2014. Oxidative dehydrogenation of ethane on dynamically rearranging supported chloride catalysts. *Journal of the American Chemical Society* 136(36):12691-12701.
- Gaspar, N. J., I. S. Pasternak, and M. Vadekar. 1974. H₂S promoted oxidative dehydrogenation of hydrocarbons in molten media. *The Canadian Journal of Chemical Engineering* 52(6):793-797.
- Gerken, J. B., and S. S. Stahl. 2015. High-potential electrocatalytic O₂ reduction with Nitroxyl/NO_x mediators: Implications for fuel cells and aerobic oxidation catalysis. *ACS Central Science* 1(5):234-243.

- German, E. D., and M. Sheintuch. 2013. Predicting CH₄ dissociation kinetics on metals: Trends, sticking coefficients, H tunneling, and kinetic isotope effect. *The Journal of Physical Chemistry C* 117(44):22811-22826.
- Gesser, H. D., N. R. Hunter, and C. B. Prakash. 1985. The direct conversion of methane to methanol by controlled oxidation. *Chemical Reviews* 85(4):235-244.
- Ghanta, M., T. Ruddy, D. Fahey, D. Busch, and B. Subramaniam. 2013. Is the liquid-phase H₂O₂-based ethylene oxide process more economical and greener than the gas-phase O₂-based silver-catalyzed process? *Industrial & Engineering Chemistry Research* 52(1):18-29.
- Goldman, A. S., A. H. Roy, Z. Huang, R. Ahuja, W. Schinski, and M. Brookhart. 2006. Catalytic alkane metathesis by tandem alkane dehydrogenation-olefin metathesis. *Science* 312(5771):257-261.
- Goldman, A. S., M. Brookhart, A. H. Roy, R. Ahuja, and Z. Huang. 2011. Dual catalyst system for alkane metathesis. Filed and issued.
- Groothaert, M. H., P. J. Smeets, B. F. Sels, P. A. Jacobs, and R. A. Schoonheydt. 2005. Selective oxidation of methane by the bis(μ -oxo)dicopper core stabilized on ZSM-5 and mordenite zeolites. *Journal of the American Chemical Society* 127(5):1394-1395.
- Grundner, S., M. A. C. Markovits, G. Li, M. Tromp, E. A. Pidko, E. J. M. Hensen, A. Jentys, M. Sanchez-Sanchez, and J. A. Lercher. 2015. Single-site trinuclear copper oxygen clusters in mordenite for selective conversion of methane to methanol. *Nature Communications* 6:7546.
- Guo, X., G. Fang, G. Li, H. Ma, H. Fan, L. Yu, C. Ma, X. Wu, D. Deng, M. Wei, D. Tan, R. Si, S. Zhang, J. Li, L. Sun, Z. Tang, X. Pan, and X. Bao. 2014. Direct, nonoxidative conversion of methane to ethylene, aromatics, and hydrogen. *Science* 344(6184):616-619.
- Hammond, C., M. M. Forde, M. H. Ab Rahim, A. Thetford, Q. He, R. L. Jenkins, N. Dimitratos, J. A. Lopez-Sanchez, N. F. Dummer, D. M. Murphy, A. F. Carley, S. H. Taylor, D. J. Willock, E. E. Stangland, J. Kang, H. Hagen, C. J. Kiely, and G. J. Hutchings. 2012. Direct catalytic conversion of methane to methanol in an aqueous medium by using copper-promoted Fe-ZSM-5. *Angewandte Chemie, International Edition in English* 51(21):5129-5133.
- Hammond, C., N. Dimitratos, J. A. Lopez-Sanchez, R. L. Jenkins, G. Whiting, S. A. Kondrat, M. H. ab Rahim, M. M. Forde, A. Thetford, H. Hagen, E. E. Stangland, J. M. Moulijn, S. H. Taylor, D. J. Willock, and G. J. Hutchings. 2013. Aqueous-phase methane oxidation over FeMFI zeolites; promotion through isomorphous framework substitution. *ACS Catalysis* 3(8):1835-1844.
- Hashiguchi, B. G., S. M. Bischof, M. M. Konnick, and R. A. Periana. 2012. Designing catalysts for functionalization of unactivated C-H bonds based on the CH activation reaction. *Accounts of Chemical Research* 45(6):885-898.
- Hinsen, W. W., and M. Baerns. 1983. Oxidative coupling of methane to C₂ hydrocarbons in the presence of different catalysts. *Chemiker-Zeitung* 107:223-226.
- Holmen, A. 2009. Direct conversion of methane to fuels and chemicals. *Catalysis Today* 142(1-2):2-8.
- Hristov, I. H., and T. Ziegler. 2003. The possible role of SO₃ as an oxidizing agent in methane functionalization by the catalytica process. A density functional theory study. *Organometallics* 22(8):1668-1674.

- Jira, R. 2009. Acetaldehyde from ethylene: A retrospective on the discovery of the Wacker process. *Angewandte Chemie, International Edition in English* 48(48):9034-9037.
- Joglekar, M., V. Nguyen, S. Pylypenko, C. Ngo, Q. Li, M. E. O'Reilly, T. S. Gray, W. A. Hubbard, T. B. Gunnoe, A. M. Herring, and B. G. Trewyn. 2016. Organometallic complexes anchored to conductive carbon for electrocatalytic oxidation of methane at low temperature. *Journal of the American Chemical Society* 138(1):116-125.
- Jones, C. A., J. J. Leonard, and J. A. Sofranko. 1984. Methane conversion. Filed and issued.
- Jones, G., J. G. Jakobsen, S. S. Shim, J. Kleis, M. P. Andersson, J. Rossmeisl, F. Abild-Pedersen, T. Bligaard, S. Helveg, B. Hinnemann, J. R. Rostrup-Nielsen, I. Chorkendorff, J. Sehested, and J. K. Nørskov. 2008. First principles calculations and experimental insight into methane steam reforming over transition metal catalysts. *Journal of Catalysis* 259(1):147-160.
- Jones, M. 2016. "Overview of the Shale Gas Boom and its Impact on the Chemical Industry." Presented at the Board on Chemical Sciences and Technology Workshop on The Changing Landscape of Hydrocarbon Feedstocks for Chemical Production: Implications for Catalysis, Washington, DC, March 7-9, 2016.
- Kado, S., K. Urasaki, Y. Sekine, and K. Fujimoto. 2003. Direct conversion of methane to acetylene or syngas at room temperature using non-equilibrium pulsed discharge. *Fuel* 82(11):1377-1385.
- Kalyuzhnaya, M. G., A. W. Puri, and M. E. Lidstrom. 2015. Metabolic engineering in methanotrophic bacteria. *Metabolic Engineering* 29:142-152.
- Katsaounis, A. 2010. Recent developments and trends in the electrochemical promotion of catalysis (epoc). *Journal of Applied Electrochemistry* 40(5):885-902.
- Keller, A. 2012. NGL 101- The Basics. Available at http://www.eia.gov/conference/ngl_virtual/eia-ngl_workshop-anne-keller.pdf [accessed June 2016].
- Keller, G. E., and M. M. Bhasin. 1982. Synthesis of ethylene via oxidative coupling of methane: I. Determination of active catalysts. *Journal of Catalysis* 73(1):9-19.
- Kiatkittipong, W., T. Tagawa, S. Goto, S. Assabumrungrat, and P. Praserthdam. 2004. Oxidative coupling of methane in the LSM/YSZ/LaAlO₃ SOFC reactor. *Journal of Chemical Engineering of Japan* 37(12):1461-1470.
- Koirala, R., R. Buechel, F. Krumeich, S. E. Pratsinis, and A. Baiker. 2015. Oxidative dehydrogenation of ethane with CO₂ over flame-made Ga-loaded TiO₂. *ACS Catalysis* 5(2):690-702.
- Kumar, C. P., S. Gaab, T. E. Muller, and J. A. Lercher. 2008. Oxidative dehydrogenation of light alkanes on supported molten alkali metal chloride catalysts. *Topics in Catalysis* 50(1):156-167.
- Kwapien, K., J. Paier, J. Sauer, M. Geske, U. Zavyalova, R. Horn, P. Schwach, A. Trunschke, and R. Schlogl. 2014. Sites for methane activation on lithium-doped magnesium oxide surfaces. *Angewandte Chemie, International Edition in English* 53(33):8774-8778.
- Labinger, J. A., and J. E. Bercaw. 2002. Understanding and exploiting C-H bond activation. *Nature* 417(6888):507-514.
- . 2015. Mechanistic studies on the Shilov system: A retrospective. *Journal of Organometallic Chemistry* 793:47-53.
- Lee, B., and T. Hibino. 2011. Efficient and selective formation of methanol from methane in a fuel cell-type reactor. *Journal of Catalysis* 279(2):233-240.

- Lercher, J. 2016. “Lighter Feedstocks—Implications and chances for catalysis.” Presented at the Board on Chemical Sciences and Technology Workshop on The Changing Landscape of Hydrocarbon Feedstocks for Chemical Production: Implications for Catalysis, Washington, DC, March 7-9, 2016.
- Levan, T., M. Che, J. M. Tatibouet, and M. Kermarec. 1993. Infrared study of the formation and stability of $\text{La}_2\text{O}_2\text{CO}_3$ during the oxidative coupling of methane on La_2O_3 . *Journal of Catalysis* 142(1):18-26.
- Lieberman, R. L., and A. C. Rosenzweig. 2005. Crystal structure of a membrane-bound metalloenzyme that catalyses the biological oxidation of methane. *Nature* 434(7030):177-182.
- Lin, C. H., K. D. Campbell, J. X. Wang, and J. H. Lunsford. 1986. Oxidative dimerization of methane over lanthanum oxide. *Journal of Physical Chemistry* 90(4):534-537.
- Liu, S., L. Wang, R. Ohnishi, and M. Ichikawa. 1999. Bifunctional catalysis of Mo/HZSM-5 in the dehydroaromatization of methane to benzene and naphthalene XAFS/TG/DTA/MASS/FTIR characterization and supporting effects. *Journal of Catalysis* 181(2):175-188.
- Liu, S., K. T. Chuang, and J.-L. Luo. 2016. Double-layered perovskite anode with in situ exsolution of a Co–Fe alloy to cogenerate ethylene and electricity in a proton-conducting ethane fuel cell. *ACS Catalysis* 6(2):760-768.
- Lorkovic, I. M., A. Yilmaz, G. A. Yilmaz, X.-P. Zhou, L. E. Laverman, S. Sun, D. J. Schaefer, M. Weiss, M. L. Noy, C. I. Cutler, J. H. Sherman, E. W. McFarland, G. D. Stucky, and P. C. Ford. 2004. A novel integrated process for the functionalization of methane and ethane: Bromine as mediator. *Catalysis Today* 98(1–2):317-322.
- Louis, C., T. L. Chang, M. Kermarec, T. L. Van, J. M. Tatibouët, and M. Che. 1993. EPR study of the stability of the O_2^- species on La_2O_3 and of their role in the oxidative coupling of methane. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 72:217-228.
- Lunsford, J. H. 1995. The catalytic oxidative coupling of methane. *Angewandte Chemie, International Edition in English* 34(9):970-980.
- . 2000. Catalytic conversion of methane to more useful chemicals and fuels: A challenge for the 21st century. *Catalysis Today* 63(2-4):165-174.
- Lyons, T. W., D. Guironnet, M. Findlater, and M. Brookhart. 2012. Synthesis of p-xylene from ethylene. *Journal of the American Chemical Society* 134(38):15708-15711.
- Marafee, A., C. Liu, G. Xu, R. Mallinson, and L. Lobban. 1997. An experimental study on the oxidative coupling of methane in a direct current corona discharge reactor over Sr/ La_2O_3 catalyst. *Industrial & Engineering Chemistry Research* 36(3):632-637.
- Maughon, B. 2016. “Methane to Ethylene: Drivers, History, Challenges, and Current Developments.” Presented at the Board on Chemical Sciences and Technology Workshop on The Changing Landscape of Hydrocarbon Feedstocks for Chemical Production: Implications for Catalysis, Washington, DC, March 7-9, 2016.
- McFarland, E. 2016. “Activation of Natural Gas Using Nontraditional Oxidants.” Presented at the Board on Chemical Sciences and Technology Workshop on The Changing Landscape of Hydrocarbon Feedstocks for Chemical Production: Implications for Catalysis, Washington, DC, March 7-9, 2016.
- Melzer, D., P. Xu, D. Hartmann, Y. Zhu, N. D. Browning, M. Sanchez-Sanchez, and J. A. Lercher. 2016. Atomic-scale determination of active facets on the MoVTeNb oxide M1

- phase and their intrinsic catalytic activity for ethane oxidative dehydrogenation. *Angewandte Chemie, International Edition in English*.
- Mukhopadhyay, S., M. Zerella, and A. T. Bell. 2005. A high-yield, liquid-phase approach for the partial oxidation of methane to methanol using SO₃ as the oxidant. *Advanced Synthesis & Catalysis* 347(9):1203-1206.
- Oshima, K., T. Shinagawa, M. Haraguchi, and Y. Sekine. 2013. Low temperature hydrogen production by catalytic steam reforming of methane in an electric field. *International Journal of Hydrogen Energy* 38(7):3003-3011.
- Palkovits, R., M. Antonietti, P. Kuhn, A. Thomas, and F. Schüth. 2009. Solid catalysts for the selective low-temperature oxidation of methane to methanol. *Angewandte Chemie International Edition in English* 48(37):6909-6912.
- Palmer, M. S., M. Neurock, and M. M. Olken. 2002. Periodic density functional theory study of methane activation over La₂O₃: Activity of O²⁻, O⁻, O₂²⁻, oxygen point defect, and Sr²⁺-doped surface sites. *Journal of the American Chemical Society* 124(28):8452-8461.
- Peng, Z., F. Somodi, S. Helveg, C. Kisielowski, P. Specht, and A. T. Bell. 2012. High-resolution in situ and ex situ TEM studies on graphene formation and growth on Pt nanoparticles. *Journal of Catalysis* 286:22-29.
- Periana, R. A., D. J. Taube, E. R. Evitt, D. G. Loffler, P. R. Wentzcek, G. Voss, and T. Masuda. 1993. A mercury-catalyzed, high-yield system for the oxidation of methane to methanol. *Science* 259(5093):340-343.
- Periana, R. A., D. J. Taube, S. Gamble, H. Taube, T. Satoh, and H. Fujii. 1998. Platinum catalysts for the high-yield oxidation of methane to a methanol derivative. *Science* 280(5363):560-564.
- Periana, R. A., O. Mironov, D. Taube, G. Bhalla, and C. Jones. 2003. Catalytic, oxidative condensation of CH₄ to CH₃COOH in one step via CH activation. *Science* 301(5634):814-818.
- Porosoff, M. D., M. N. Myint, S. Kattel, Z. Xie, E. Gomez, P. Liu, and J. G. Chen. 2015. Identifying different types of catalysts for CO₂ reduction by ethane through dry reforming and oxidative dehydrogenation. *Angewandte Chemie, International Edition in English* 54(51):15501-15505.
- Quddus, M. R., Y. Zhang, and A. K. Ray. 2010. Multi-objective optimization in solid oxide fuel cell for oxidative coupling of methane. *Chemical Engineering Journal* 165(2):639-648.
- Ramos, R., M. Menéndez, and J. Santamaría. 2000. Oxidative dehydrogenation of propane in an inert membrane reactor. *Catalysis Today* 56(1-3):239-245.
- Rebeilleau-Dassonneville, M., S. Rosini, A. C. v. Veen, D. Farrusseng, and C. Mirodatos. 2005. Oxidative activation of ethane on catalytic modified dense ionic oxygen conducting membranes. *Catalysis Today* 104(2-4):131-137.
- Rust, F. F., and W. E. Vaughan. 1949. Oxidation of hydrocarbons catalyzed by hydrogen bromide - Summary. *Industrial & Engineering Chemistry* 41(11):2595-2597.
- Saadi, S., F. Abild-Pedersen, S. Helveg, J. Sehested, B. Hinnemann, C. C. Appel, and J. K. Nørskov. 2010. On the role of metal step-edges in graphene growth. *The Journal of Physical Chemistry C* 114(25):11221-11227.
- Sadow, A. D., and T. D. Tilley. 2003. Homogeneous catalysis with methane. A strategy for the hydromethylation of olefins based on the nondegenerate exchange of alkyl groups and sigma-bond metathesis at scandium. *Journal of the American Chemical Society* 125(26):7971-7977.

- Salehi, M.-S., M. Askarishahi, H. R. Godini, O. Görke, and G. Wozny. 2016. Sustainable process design for oxidative coupling of methane (OCM): Comprehensive reactor engineering via computational fluid dynamics (CFD) analysis of OCM packed-bed membrane reactors. *Industrial & Engineering Chemistry Research*.
- Sanborn, C. E., E. A. Anderson, and H. H. Engel. 1968. Iodinative dehydrogenation and iodine recovery. US3405195 A, filed October 8, 1968, and issued.
- Schäfer, R., M. Noack, P. Kölsch, M. Stöhr, and J. Caro. 2003. Comparison of different catalysts in the membrane-supported dehydrogenation of propane. *Catalysis Today* 82(1-4):15-23.
- Schwach, P., M. G. Willinger, A. Trunschke, and R. Schlögl. 2013. Methane coupling over magnesium oxide: How doping can work. *Angewandte Chemie, International Edition in English* 52(43):11381-11384.
- Schwach, P., W. Frandsen, M.-G. Willinger, R. Schlögl, and A. Trunschke. 2015. Structure sensitivity of the oxidative activation of methane over MgO model catalysts: I. Kinetic study. *Journal of Catalysis* 329:560-573.
- Sehested, J. 2006. Four challenges for nickel steam-reforming catalysts. *Catalysis Today* 111(1-2):103-110.
- Sekine, Y., K. Tanaka, M. Matsukata, and E. Kikuchi. 2009. Oxidative coupling of methane on Fe-doped La₂O₃ catalyst. *Energy & Fuels* 23(2):613-616.
- Sekine, Y., M. Haraguchi, M. Matsukata, and E. Kikuchi. 2011. Low temperature steam reforming of methane over metal catalyst supported on Ce_xZr_{1-x}O₂ in an electric field. *Catalysis Today* 171(1):116-125.
- Shah, N. N., M. L. Hanna, and R. T. Taylor. 1996. Batch cultivation of *Methylosinus trichosporium* OB3b: V. Characterization of poly-β-hydroxybutyrate production under methane-dependent growth conditions. *Biotechnology and Bioengineering* 49:161-171.
- Shalygin, A., E. Paukshtis, E. Kovalyov, and B. Bal'zhinimaev. 2013. Light olefins synthesis from C1-C2 paraffins via oxychlorination processes. *Frontiers of Chemical Science and Engineering* 7(3):279-288.
- Shilov, A. E. and G. B. Shul'pin. 1997. Activation of C-H bonds by metal complexes. *Chemical Reviews* 97(8): 2879-2932.
- Silberova, B., M. Fathi, and A. Holmen. 2004. Oxidative dehydrogenation of ethane and propane at short contact time. *Applied Catalysis A: General* 276(1-2):17-28.
- Simon, U., O. Görke, A. Berthold, S. Arndt, R. Schomäcker, and H. Schubert. 2011. Fluidized bed processing of sodium tungsten manganese catalysts for the oxidative coupling of methane. *Chemical Engineering Journal* 168(3):1352-1359.
- Somodi, F., Z. Peng, A. B. Getsoian, and A. T. Bell. 2011. Effects of the synthesis parameters on the size and composition of Pt–Sn nanoparticles prepared by the polyalcohol reduction method. *The Journal of Physical Chemistry C* 115(39):19084-19090.
- Somodi, F., S. Werner, Z. Peng, A. B. Getsoian, A. N. Mlinar, B. S. Yeo, and A. T. Bell. 2012. Size and composition control of Pt-In nanoparticles prepared by seed-mediated growth using bimetallic seeds. *Langmuir* 28(7):3345-3349.
- Soorholtz, M., R. J. White, T. Zimmermann, M.-M. Titirici, M. Antonietti, R. Palkovits, and F. Schuth. 2013. Direct methane oxidation over Pt-modified nitrogen-doped carbons. *Chemical Communications* 49(3):240-242.
- Soulivong, D., C. Copéret, J. Thivolle-Cazat, J.-M. Basset, B. M. Maunders, R. B. A. Pardy, and G. J. Sunley. 2004. Cross-metathesis of propane and methane: A catalytic reaction of C-C

- bond cleavage of a higher alkane by methane. *Angewandte Chemie International Edition in English* 43(40):5366-5369.
- Spinner, N., and W. E. Mustain. 2013. Electrochemical methane activation and conversion to oxygenates at room temperature. *Journal of the Electrochemical Society* 160(11):F1275-F1281.
- Stahl, S. 2016. "Homogeneous Catalysis for C-H Activation and Other Approaches to Shale Gas Utilization." Presented at the Board on Chemical Sciences and Technology Workshop on The Changing Landscape of Hydrocarbon Feedstocks for Chemical Production: Implications for Catalysis, Washington, DC, March 7-9, 2016.
- Stansch, Z., L. Mleczko, and M. Baerns. 1997. Comprehensive kinetics of oxidative coupling of methane over the La₂O₃/CaO catalyst. *Industrial & Engineering Chemistry Research* 36(7):2568-2579.
- Strong, P. J., S. Xie, and W. P. Clarke. 2015. Methane as a resource: Can the methanotrophs add value? *Environmental Science & Technology* 49(7):4001-4018.
- Subramaniam, B. 2016. "Environmental Impacts." Presented at the Board on Chemical Sciences and Technology Workshop on The Changing Landscape of Hydrocarbon Feedstocks for Chemical Production: Implications for Catalysis, Washington, DC, March 7-9, 2016.
- Sun, P., G. Siddiqi, W. C. Vining, M. Chi, and A. T. Bell. 2011. Novel Pt/Mg(In)(Al)O catalysts for ethane and propane dehydrogenation. *Journal of Catalysis* 282(1):165-174.
- Tabata, K., Y. Teng, T. Takemoto, E. Suzuki, M. A. Bañares, M. A. Peña, and J. L. G. Fierro. 2002. Activation of methane by oxygen and nitrogen oxides. *Catalysis Reviews* 44(1):1-58.
- Tomás, R. A., J. C. M. Bordado, and J. F. P. Gomes. p-Xylene oxidation to terephthalic acid: A literature review oriented toward process optimization and development. *Chemical Reviews* 113(10):7421-7469.
- Upham, D. C., M. J. Gordon, H. Metiu, and E. W. McFarland. 2016. Halogen-mediated oxidative dehydrogenation of propane using iodine or molten lithium iodide. *Catalysis Letters* 146(4):744-754.
- U.S. International Energy Agency, International Council of Chemical Associations, and DECHEMA. 2013. Technology Roadmap—Energy and GHG Reductions in the Chemical Industry via Catalytic Processes. Available at www.iea.org/publications/freepublications/publication/Chemical_Roadmap_2013_Final_WEB.pdf [accessed March 7, 2016]. Copyright © 2013 OECD/IEA, 9 rue de la Fédération, 75739 Paris Cedex 15, France and The International Association for Chemical Associations, [Avenue E. Van Nieuwenhuyse 4, box 1, B-1160 Brussels, Belgium] and Gesellschaft für Chemische Technik und Biotechnologie e.V. (DECHEMA), [Theodor-Heuss-Allee 25, 60486 Frankfurt am Main]. License: www.iea.org/t&c.
- Wang, S.-G., X.-Y. Liao, J. Hu, D.-B. Cao, Y.-W. Li, J. Wang, and H. Jiao. 2007. Kinetic aspect of CO₂ reforming of CH₄ on Ni(111): A density functional theory calculation. *Surface Science* 601(5):1271-1284.
- Wang, W., A. D. Liang, and S. J. Lippard. 2015. Coupling oxygen consumption with hydrocarbon oxidation in bacterial multicomponent monooxygenases. *Accounts of Chemical Research* 48(9):2632-2639.
- Wang, Y., Y. Takahashi, and Y. Ohtsuka. 1999. Carbon dioxide as oxidant for the conversion of methane to ethane and ethylene using modified CeO₂ catalysts. *Journal of Catalysis* 186(1):160-168.

- Wei, J., and E. Iglesia. 2004. Isotopic and kinetic assessment of the mechanism of reactions of CH₄ with CO₂ or H₂O to form synthesis gas and carbon on nickel catalysts. *Journal of Catalysis* 224(2):370-383.
- Woertink, J. S., P. J. Smeets, M. H. Groothaert, M. A. Vance, B. F. Sels, R. A. Schoonheydt, and E. I. Solomon. 2009. A [Cu₂O]²⁺ core in CuZSM-5, the active site in the oxidation of methane to methanol. *Proceedings of the National Academy of Sciences* 106(45):18908-18913.
- Wood, B. R., J. A. Reimer, M. T. Janicke, and K. C. Ott, and A. T. Bell. 2004. Methanol formation of Fe/Al-MFI via the oxidation of methane by nitrous oxide. *Journal of Catalysis* 225:300-306.
- Wu, J., Z. Peng, and A. T. Bell. 2014a. Effects of composition and metal particle size on ethane dehydrogenation over Pt_xSn_{100-x}/Mg(Al)O (70 ≤ x ≤ 100). *Journal of Catalysis* 311:161-168.
- Wu, J., Z. Peng, P. Sun, and A. T. Bell. 2014b. N-butane dehydrogenation over Pt/Mg(In)(Al)O. *Applied Catalysis A: General* 470:208-214.
- Wu, J., S. Mallikarjun Sharada, C. Ho, A. W. Hauser, M. Head-Gordon, and A. T. Bell. 2015. Ethane and propane dehydrogenation over Pt/Mg(In)(Al)O. *Applied Catalysis A: General* 506:25-32.
- Wu, J., S. Helveg, S. Ullman, Z. Peng, and A. T. Bell. 2016. Growth of encapsulating carbon on supported Pt nanoparticles studied by in situ TEM. *Journal of Catalysis* 338:295-304.
- Yildiz, M., Y. Aksu, U. Simon, K. Kailasam, O. Goerke, F. Rosowski, R. Schomacker, A. Thomas, and S. Arndt. 2014a. Enhanced catalytic performance of Mn_xO_y-Na₂WO₄/SiO₂ for the oxidative coupling of methane using an ordered mesoporous silica support. *Chemical Communications (Cambridge)* 50(92):14440-14442.
- Yildiz, M., U. Simon, T. Otremba, Y. Aksu, K. Kailasam, A. Thomas, R. Schomäcker, and S. Arndt. 2014b. Support material variation for the Mn_xO_y-Na₂WO₄/SiO₂ catalyst. *Catalysis Today* 228:5-14.
- Zavala-Araiza, D., D. R. Lyon, R. A. Alvarez, K. J. Davis, R. Harriss, S. C. Herndon, A. Karion, E. A. Kort, B. K. Lamb, X. Lan, A. J. Marchese, S. W. Pacala, A. L. Robinson, P. B. Shepson, C. Sweeney, R. Talbot, A. Townsend-Small, T. I. Yacovitch, D. J. Zimmerle, and S. P. Hamburg. 2015. Reconciling divergent estimates of oil and gas methane emissions. *Proceedings of the National Academy of Sciences* 112(51):15597-15602.
- Zavyalova, U., Holena, M., Schlogl, R., and M. Baerns. 2011. Statistical Analysis of Past Catalytic Data on Oxidative Methane Coupling for New Insights into the Composition of High-Performance Catalysts. *ChemCatChem*. 3: 1935-1947. Copyright Wiley-VCH Verlag GmbH & Co. KGaA.
- Zboray, M., A. T. Bell, and E. Iglesia. 2009. Role of C-H bond strength in the rate and selectivity of oxidative dehydrogenation of alkanes. *The Journal of Physical Chemistry C* 113(28):12380-12386.
- Zhang, A., S. Sun, Z. J. A. Komon, N. Osterwalder, S. Gadewar, P. Stoimenov, D. J. Auerbach, G. D. Stucky, and E. W. McFarland. 2011. Improved light olefin yield from methyl bromide coupling over modified SAPO-34 molecular sieves. *Physical Chemistry Chemical Physics* 13(7):2550-2555.
- Zhu, Q., S. L. Wegener, C. Xie, O. Uche, M. Neurock, and T. J. Marks. 2013. Sulfur as a selective “soft” oxidant for catalytic methane conversion probed by experiment and theory. *Nature Chemistry* 5(2):104-109.