



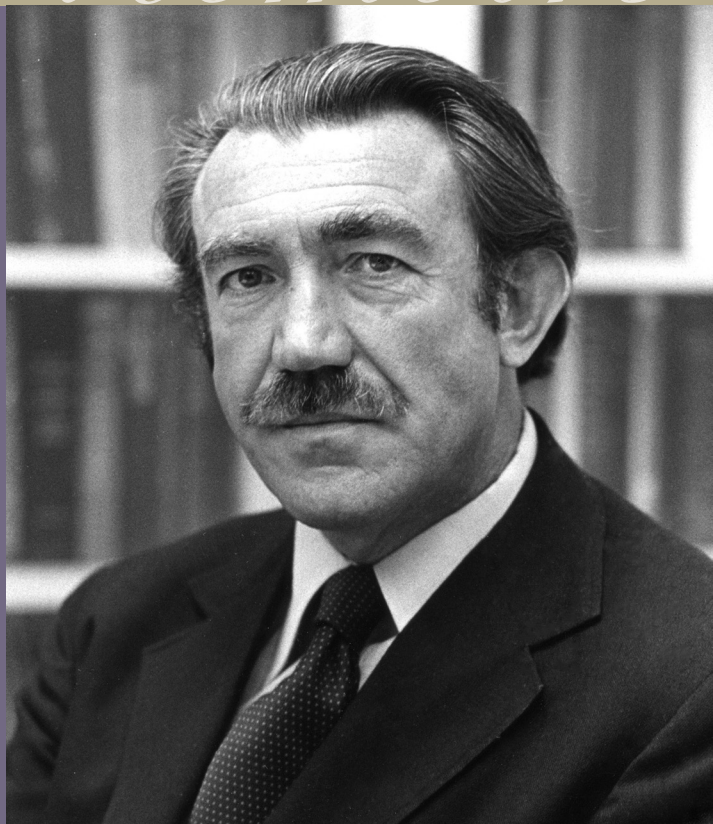
Michel Boudart

1924–2012

BIOGRAPHICAL

Memoirs

*A Biographical Memoir by
Ricardo B. Levy,
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James A. Cusumano,
and Enrique Iglesia*



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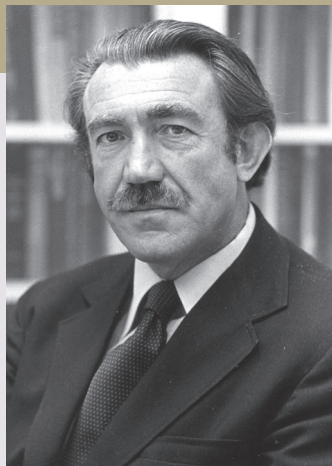
NATIONAL ACADEMY OF SCIENCES

MICHEL BOUDART

June 18, 1924–May 2, 2012

Elected to the NAS, 1975

Michel Boudart was born in Brussels, Belgium, into a family steeped in the chemical industry. His father, François Boudart, was president of the Fédération des Industries Chimiques de Belgique and closely associated with the Union Chimique Belge, a major international chemical and pharmaceutical company. Michel weathered the difficult occupation years during World War II as a young student, never wavering from his academic pursuits. After graduating from high school, he volunteered as a stretcher-bearer with the Red Cross, primarily to avoid conscription into the German army. Michel had been accepted to the University of Louvain but it was closed during the war, so he continued his studies privately. When the university reopened in 1944, he entered its Department of Chemistry and graduated in record time, receiving his B.S. in chemistry in 1945 and his M.S. in 1947.



A handwritten signature in dark ink, which appears to read 'M Boudart'.

By Ricardo B. Levy,
Jim Dumesic,
James A. Cusumano,
and Enrique Iglesia

Michel's family urged him to complete his Ph.D. in Belgium and take a prominent place in the Belgian chemical world, but he had other plans. 1912, twelve years before Michel was born, a young British scientist was studying the nature of adsorption and chemical reactivity on metallic surfaces at the Nobel Institute in Stockholm. His name was Hugh Taylor. His professor was Svante Arrhenius, recipient of the 1903 Nobel Prize in Chemistry. Under Arrhenius' direction, Hugh Taylor would soon become one of the fathers of a scientific field that spearheaded the growth of industrial chemistry: Catalysis. The key conceptual framework pioneered by Taylor highlighted the essential role of specific "active sites" defining catalytic action on the catalytic surface. This framework became the basis for Taylor's work when he moved to Princeton University in 1914. Hugh Taylor was knighted by both Pope Pius XII and Queen Elizabeth in 1953 for his work on the Manhattan Project, but of greater import to our story of Michel Boudart was Taylor's earlier appointment as Commander of the Belgian Order of Leopold II in 1937, based on his landmark contributions to the field of chemical catalysis.

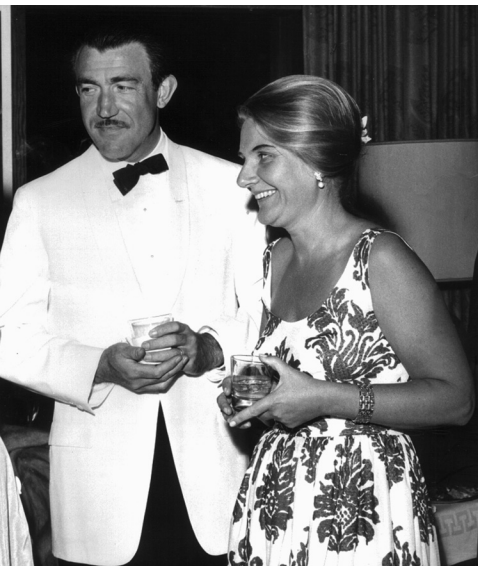
During his master's studies, Michel had learned of the important work of Sir Hugh Taylor and decided to go to the United States and continue his graduate studies at Princeton University, where Taylor, who by then was chair of the chemistry department, would personally guide his work. Michel was particularly intrigued by the important role of catalysts in chemical reactions.

Chemical kinetics and the role of catalysis was an early interest of Taylor's, starting with his work in 1913 at the Technische Hochschule in Hannover. He was a frequent visitor at other laboratories in Europe including the Kaiser Wilhelm Institute in Berlin-Dahlem, Germany, where a group worked under the direction of Fritz Haber, the 1918 Nobel Laureate in Chemistry who conducted the first successful synthesis of ammonia in 1913. It was at the Kaiser Wilhelm Institute (later renamed the Fritz Haber Institute) that Taylor met Setsuro Tamaru, a young scientist visiting from Japan who was also interested in the chemistry of nitrogen. At the Kaiser Wilhelm Institute, Tamaru and his colleagues interacted with eminent scientific minds in the fields of Chemistry and Physics, the most prominent being Albert Einstein. Many of these scientist, Tamaru and Einstein included, would become touchstones in the fascinating mosaic of Michel Boudart's life, as the result of his choice to work with Hugh Taylor at Princeton. Michel and his family would be frequent guests at Einstein's private violin recitals in Princeton. Setsuro Tamaru's son, Kenzi, who spent three years in Princeton after his PhD from the Tokyo Institute of Technology, became a life long friend and collaborator of Michel's as he became the central figure in the development of catalysis in Japan¹.

After receiving his Ph.D. in 1950, again despite persistent family pressure to return to Belgium, Michel decided to build a life in the United States and accept a faculty position at Princeton as research associate at the Forrestal Center. This decision set the stage for the profound impact that he would have on the field of catalysis for nearly half a century.

In 1953, Michel became assistant director of Project SQUID, an effort headed by John Fenn (2002 Nobel Prize in Chemistry) to develop and improve pulsejet and rocket engines for the U.S. Office of Naval Research. Michel joined the Princeton Department of Chemical Engineering as assistant professor in 1954, and in 1958 he was promoted to associate professor.

1 Hideko Tamaru Oyama "Setsuro Tamaru and Fritz Haber: Japan and Germany in Science and Technology," Chem. Rec. 2015, 15, 535-549



Marina Boudart's radiance shines through in this photograph of Marina and Michel at an event in Berkeley, California, circa 1960.

Another decision that Michel made shortly after his arrival in the United States also had important ramifications: He convinced another very special Belgian to join him—his fiancée Marina d'Haese, whom he had met through a Catholic youth group in Louvain—and they were married on December 27, 1948, at Taylor's home.

Marina became an integral part of the Boudart legacy that touched so many of us. She is fondly remembered as the kind and nurturing hostess of many get-togethers at the Boudart home, whether with friends, or graduate students, or both. While Michel never lost the stern bearing of a European academic, the warm and gregarious Marina considerably softened his sometimes-daunting professorial edge.

All of us who knew Michel never forgot his formidable European heritage: His strong Belgian accent, erect posture, and serious demeanor were legendary. One of his early Princeton faculty colleagues, Bill Schowalter, described Michel as

exuding European urbanity. As young faculty members, Bill and Michel, along with Leon Lapidus, shared adjoining offices on the third floor of the old Chemistry Building, an area accessed by a steep wooden stairway. "My office was nearest to the stairs," Bill recollected. "From the sound, I could usually tell who was coming or leaving our floor. Dick Wilhelm, the department chair, would bound up and down two stairs at a time. I don't recall Leon's signature, but Michel's was a regal step of absolute uniform cadence for all three floors. In like manner, his speech was always carefully measured, and his words were chosen both for meaning and elegance."

As restrained and professorial as Michel was on the surface, inside was a kindly mentor with an enormous reservoir of support for his students and a razor-sharp mind that ensured the emerging field of catalysis would meet the most rigorous of scientific standards. His keen insights, evident throughout his career, were already manifested even before he finished his Ph.D. Michel published a pivotal article in the

Journal of the American Chemical Society in 1950 that extended Hugh Taylor's pioneering concepts of active sites on catalytic surfaces to incorporate early concepts of the electronic structure of metals being studied by Nobel Laureate Linus Pauling at CalTech, who became Michel's close friend during his later years at Stanford (Boudart 1950).

In spring 1959, Michel spent a sabbatical at the University of California, Berkeley, at the encouragement of Berkeley's chemical engineering professor Andreas Acrivos, who met him at a meeting of the American Institute of Chemical Engineers. In 1961, Michel was invited to join the Berkeley faculty. Meanwhile, Stanford University was in the process of building its chemical engineering department under the leadership of David Mason. Acrivos was attracted to Stanford in 1962, and he in turn influenced Michel to join the department there in 1964. Acrivos and Boudart consequently became the nucleus of the growth that brought Stanford's Department of Chemical Engineering to worldwide prominence, and Stanford remained Michel's home for the rest of his professional career. He was named the first William M. Keck Senior Professor of Chemical Engineering, and became Professor Emeritus of Chemical Engineering upon his retirement in 1994.

Off campus, the Boudart home became a focal point of intellectual life in the Stanford community. Daughter Iris Boudart recollected, "I remember my friends being very impressed when they attended our son's christening at my parents' home. Crowded around the bar with Michel were five Nobel Laureates: Pauling (Chemistry 1954, Peace 1962), Paul Flory (Chemistry 1974), Henri Taube (Chemistry 1983), Dick Taylor (Physics 1990), and Milton Friedman (Economics 1976)." This was a treat for Michel's students too, who were always included as an integral part of these gatherings.

Michel passed away on May 2, 2012, in Palo Alto, CA. He had been an international ambassador for the field of catalysis, and the scores of doctoral candidates, postdoctoral researchers, and visiting scientists he mentored would continue leading and shaping the field throughout the world, even to its remote corners.

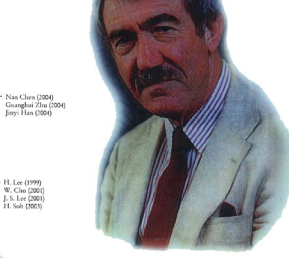
Thus Michel's most telling legacy was likely his scientific family. Shortly after his retirement in 1994, with the help of his long-time assistant Lindi Press, University of Wisconsin Professor Jim Dumesic (who obtained his Ph.D. under Michel in 1974) put together a family tree listing Michel's 69 scientific children and 414 grandchildren. This impressive legacy is shown in the figure on page 6.

Michel Boudart — Family

Michel Boudart Married 6/18/24 Marina D'Haese 2/28/25
Marc 6/5/59 Boudoin 9/2/69 Iris 6/6/71 Philip 8/1/74

Academic Family

- William J. Hindegar (Princeton 1959)
E. Stanley Lee (Princeton 1960)
Kin Tai (Princeton 1960)
Robert M. Koros (Princeton 1961)
E. James Nowak (Princeton 1962)
Ronald P. Andres (Princeton 1963)
John B. Anderson (Princeton 1964)
James C. Berg (Berkeley 1964)
Richard Getzinger (Berkeley 1964)
Shelby Kurzius (Berkeley 1964)
Robert J. Madix (Berkeley 1964)
Andrew J. Robell (Berkeley 1964)
Reuben P. Chambers (Berkeley 1965)
Neil A. Dougharty (Berkeley 1965)
Grady W. Harris (Berkeley 1965)
David E. Mears (Berkeley 1965)
Arthur W. Aldag, Jr. (Stanford 1968)
Salah B.T. Khammouch (Stanford 1968)
David P. Ollis (Stanford 1968)
W. Nicholas Delgas (Stanford 1969)
Huang Yun Yang (Stanford 1969)
M. A. Vannice (Stanford 1970)
Arden B. Walters (Stanford 1970)
James C. Schlatter (Stanford 1971)
Ralph A. Dall-Betta (Stanford 1972)
Ricardo B. Levy (Stanford 1972)
Frank L. Williams (Stanford 1972)
Ali Aminizadeh (Stanford 1973)
Calvin H. Bartholomew, Jr. (Stanford 1973)
Henrik Topsoe (Stanford 1973)
James A. Dumesic (Stanford 1974)
Rostam Maden (Stanford 1975)
Barrie D. Turnham (Stanford 1975)
Francis V. Hanson (Stanford 1976)
Ping-Shan Hwang (Stanford 1976)
David C. Silverman (Stanford 1976)
Yao-Lau Lam (Stanford 1978)
David Storm (Stanford 1978)
Dennis O' Rear (Stanford 1979)
William S. Borghard (Stanford 1981)
William L. Holstein (Stanford 1981)
Spyridon Ladas (Stanford 1981)
Enrique Iglesia (Stanford 1982)
Carol M. McConica (Stanford 1982)
S. Ted Oyama (Stanford 1982)
Wu-Cheng Cheng (Stanford 1984)
Shunichi Ishikawa (Stanford 1984)
Mark McDonald (Stanford 1984)
George D. Metzner (Stanford 1984)
Jorge Sanchez-Arrieta (Stanford 1984)
Jae Sung Lee (Stanford 1985)
Ryong Ryou (Stanford 1985)
Leo Volpe (Stanford 1985)
Robert S. Weber (Stanford 1985)
Guang Zhang (Stanford 1985)
Francisco Javier Rivera-Latas (Stanford 1986)
Daniel J. Sajkowski (Stanford 1986)
Mahesh G. Samant (Stanford 1986)
Eric S. Birmbaum (Stanford 1987)
Kenneth J. Lin (Stanford 1987)
Fabio H. Ribeiro (Stanford 1989)
Frederick H. Rumpf (Stanford 1987)
Robert J. Davis (Stanford 1989)
Gerald J. Guskey (Stanford 1989)
Steven M. Landry (Stanford 1989)
Gustavo P. Valenza (Stanford 1991)
Young Chai Kim (Stanford 1991)
Laurent D. Kieken (Stanford 1992)
Hüing-I (David) Su (Stanford 1992)





Michel is honored at the entrance of the Chemical Engineering Department office in the new Shriram Bioengineering and Chemical Engineering building at Stanford University. Shown here are the Boudart Scientific Family Tree and the original scroll of the wonderful poem penned by Rutherford Aris.

Over the years, Michel lectured at some of the most prestigious scientific gatherings on catalysis. It was at one of these lectures, when Michel was the 1977 recipient of the Cal Tech Lacey Lectureship, that University of Minnesota professor and 1970 Lacey Lecturer Rutherford Aris shared a wonderful poem he had penned, which captured Michel's persona.

*Lines written on hearing of a certain Lacey Lecturer**By A. N. Other*

*The Belgae, we are told by Julius C.,
 Are not much taken by philosophy
 But given rather to the martial arts
 Therewith t'impress the natives of those parts.
 Now here to prove the truth of Caesar's rule
 There comes a scholar from a neighboring school
 The shortest trip he's ever made this nonce
 So treat his non-jet-lag with tolerance.*

*Louvain, the home of neo-Thomist lore,
 Gave him to Princeton, there to learn some more – under the tutelage of
 good St Hugh –
 Of arcane alchemy than erst he knew
 As Ingenieur Civil Chimiste he served,
 With great Sr. Richard, Jacobs' period,
 Till, like the lightning, flying East to West
 Through Berkeley passed, at Stanford came to rest.*

*To chymists' minds a stern ascetic he
 Who calls reacting species A & B.
 But to the engineers he's picturesque,
 As, with panache, from his cathedral desk
 He talks of molecules as shapely friends
 With sticking coefficients at their ends.
 With the abstruse and recondite he grapples
 And turnovers, to us bespeak apples,
 To him are numbers telling o'er the way
 That molecules with catalysts will play.
 There's no experiment one can devise
 Whose outcome Boudart cannot analyce.
 This new phenomenon, he will declare,
 Is sure a case of spillover.
 Captains of mighty industries attend*

*His slightest word, for he his aid will lend
 To companies who can afford the rates
 Of Catalytica Associates.
 Awards and honors? He's had every one
 Were I to list them all I'd ne'er be done.
 It was in 1961 that he
 Inst. Lectured to the AIChE
 Since then he has Humbled, Reillyd, Sigma Xied,
 Kelleyd, Welched, Wold even Joseph Priestleyd.
 Now with a meet, indeed a wonted, grace he
 Adds to his crown the crown of all, the Lacey.*

RA (Rutherford Aris)

This poem—a perfect prelude to our discussion of Michel’s significant scientific, technological, and industrial legacy—also reflects that, deep at heart, Michel never left Belgium, even though he put down new roots elsewhere. He and his wife Marina coauthored a book titled *Modern Belgium* (Boudart and Boudart 1990), and when the King of Belgium (then Crown Prince Phillip) was a masters student in political science at Stanford he considered the Boudarts his surrogate family, frequently staying at their home. Michel was a foreign member of the Académie Royale des Sciences, des Lettres, et des Beaux-Arts de Belgique and of the Royal Belgian Academy Council for Applied Sciences.

Scientific legacy

Michel Boudart was the guiding force in the field of heterogeneous catalysis for more than 40 years with his repeated contributions to the conceptual, quantitative, and molecular understanding of fundamental catalytic chemistry. In particular, his elegantly stated concepts of quantitative reaction kinetics, his experimental observation of catalytic sites and new catalytic materials, and the activities of his former students and postdocs around the world continue to shape the field.

Few areas of chemical science have had the broad impact on quality of life that heterogeneous catalysis can claim. Knowledge of the chemical interactions of catalytic surfaces with adsorbed molecules (e.g., reactants, products, and reaction intermediates) is key to the efficient production of environmentally friendly fuels, advanced materials, and the commodity chemicals and fertilizers that have resulted in a steady growth in the world’s food supply.

While the search for Taylor's active sites in many ways defined the evolution of modern catalytic science, today's successes are rooted in concepts advanced by Boudart throughout his career. Foremost was the quantitation of catalytic-reaction kinetics, in particular the following three concepts:

- Measurement of the reaction rate in terms of *turnover frequencies*
- Specification of reaction steps by means of their reversibility and degree of *kinetic control*
- Rigorous *microkinetic analysis* to reveal the key steps in a reaction sequence and to remove artifacts that obscure the real catalytic action.

Turnover frequencies

By introducing the concept of the *turnover frequency* (molecules converted per catalytic site per second), Boudart highlighted the fact that rates could only be understood if they were normalized to the most appropriate measure of the number of active sites. Thus he pioneered rigorous protocols for (1) accurate measurement of the specific metal surface area in supported catalysts and (2) experimental methods to assure that heat and mass transfer effects would not intrude on measurements of the intrinsic reaction kinetics.

Many advances in the field can be traced to this clear articulation of the right way to collect and report reaction-rate data, which has enabled the benchmarking of rate data among laboratories. Moreover, the detailed studies of the effects of catalyst preparation on intrinsic reactivity have provided a bridge between practical catalysis and surface science. Turnover rates show, for example, that hydrogenation of cyclohexene is independent of catalyst surface structure, having the same value per surface-platinum atom both for centimeter-sized single-crystal platinum and nanometer-sized supported platinum particles. By contrast, other reactions, such as ammonia synthesis on iron, require specific arrangements of surface-metal atoms sites with many of their nearest neighbors. This type of analysis led Boudart to propose that reactions are either *facile* or *demanding*, depending on the structural requirements of each specific reaction.

Directly connected with his attention to turnover frequency and structural sensitivity was Boudart's quest to see catalytic sites directly. For example, his electron paramagnetic resonance work on MgO with Andre Delbouille, Eric Derouane, Valerio Indovina, and Arden Walters (Boudart et al. 1972) led to one of the first direct identifications of a catalytic site—in this case, a paramagnetic defect site for hydrogen activation. In an elegant

series of Mössbauer spectroscopic experiments with Nick Delgass and Bob Garten, Boudart demonstrated both the surface reconstruction of small supported iron particles in the presence of N_2 and the importance of C7 (seven coordinated metal atoms) sites for catalytic activity in ammonia synthesis (Delgass, Garten, and Boudart 1969). And a series of papers on palladium-containing catalysts showed the specific structures and kinetic effects of gold's addition to palladium, representing a step toward the design of catalysts through deliberate modification of active sites.

Boudart and his students were the first researchers to experimentally establish that small clusters of platinum supported on zeolites were inside zeolite super cages, and to determine their average size to be 5 atoms per cluster, as reported in a paper with his student Ralph Dalla Betta (Dalla Betta and Boudart 1973). These platinum clusters were shown to interact with the zeolite structure, resulting in a material with new catalytic properties. But perhaps the best example of the modification of catalytic properties was Boudart's discovery that tungsten carbides showed platinum-like properties (Levy and Boudart 1973). This work was extended to interstitial compounds of tungsten and molybdenum, and it led to the synthesis and kinetic and mechanistic evaluations of a broad range of new carbide and nitride catalytic materials. It led as well to the development of novel syntheses of catalysts by topotactic and surface-modification methods.

Degree of kinetic control

Boudart insisted that studies of catalytic reactions include measurements of the reaction kinetics (the mathematical catalytic-rate expression) under conditions of strict kinetic control. In his classic book *Kinetics of Chemical Processes* (Boudart 1968), he discussed the origins of kinetically significant steps in a catalytic sequence composed of elementary reaction events. For instance, steps following an irreversible step become insignificant in determining the rate of the overall catalytic reaction so long as the adsorbed species involved are present at low coverage. He thus outlined the use of two-step reaction schemes to derive rate equations—expressed in terms of kinetic and thermodynamic parameters having physical significance and corresponding to elementary reaction events—for describing the observed reaction kinetics.

This careful distinction between steps in the reaction scheme that are kinetically significant—as opposed to those that are kinetically insignificant because they are quasi-equilibrated or follow other steps that are irreversible—led to the concept of degree of rate control now widely referenced in the literature. It was highlighted by

Boudart's former Ph.D. student Jim Dumesic in his discussion of the topic in 2001² and used in 2016 as the basis for analysis of reaction schemes.³ By showing how catalytic reactions can be analyzed in a manner that directs attention only to those steps that are essential, and by insisting that kinetic constants be closely examined for their physical validity, Boudart taught the community the value of kinetic expressions, as well as their limitations.

Boudart also demonstrated the need to consider the energetic non-uniformity of surfaces in order to understand the catalytic behavior of structure-sensitive reactions such as ammonia synthesis. He illustrated how elementary steps can be coupled kinetically to give rise to non-equilibrium coverages of adsorbed intermediates and, in so doing, become essential in the control of selectivity. These principles, pioneered by Boudart, have evolved to allow assisted design of catalytic cycles and to provide guidance for the use of fundamental adsorption and rate constants derived from single-crystal studies. Moreover, these principles represent the foundations of modern microkinetic analysis, discussed below.

Microkinetic analysis

The adoption of microkinetic analysis by the catalysis community stemmed directly from Boudart's vision for quantifying the rates and reaction kinetics for heterogeneous catalytic reactions. *Ab initio* calculations, the availability of increasingly sophisticated tools for in situ observation of surface phenomena, and a generally greater understanding of fundamental catalytic chemistry, brought the discipline of heterogeneous catalysis to the point where the design of materials for specific catalytic functions could be contemplated and, in some cases, brought to practice. With the use of advanced computational techniques, Boudart inspired the use of coupled algebraic and differential equations to determine a proposed reaction scheme's surface coverages of adsorbed intermediates and the forward and reverse rates of individual steps, without the need for *a priori* assumptions about the kinetic relevance of specific elementary steps.

Using results from experimental studies and density functional theory calculations to determine the properties of adsorbed species and transition states, microkinetic models could be built for a broad range of practical reaction conditions. Sensitivity analyses could be carried out using these microkinetic models to identify those steps and adsorbed species

2 Dumesic, J. A. 2001. Reply to "Finding the rate-determining step in a mechanism: Comparing DeDonder relations with the 'degree of rate control.'" *Journal of Catalysis* 204:525–529.

3 Motagamwala, A. H., and J. A. Dumesic. 2016. Analysis of reaction schemes using maximum rates of constituent steps. *Proceedings of the National Academy of Sciences* 113:E2879–E2888.

that best control reactivity and selectivity for reaction conditions of interest. Such methods made possible, for the first time, the rigorous connection and benchmarking of theory and experiments in efforts to elucidate how the surface properties of a catalyst control the rates of reaction. Strategies could thus be formulated to optimize rates and selectivities.

Being a careful and rigorous experimentalist in the quantification of reaction kinetics, Boudart contended that the publication of results from microkinetic analyses should be held to the same standard as the publication of data from experiments. In particular, he insisted that all the details of the equations, the calculations of rate and thermodynamic parameters, and the methods used to solve the equations should be reported in sufficient detail to enable other researchers to repeat and thereby confirm the analysis and its conclusions. Over the past several decades, researchers around the world have carried out such microkinetic analyses of many catalytic processes, which enabled them to identify the steps and adsorbed species that control the reaction kinetics. As anticipated by Boudart, the observed reaction kinetics are in fact typically controlled by a limited number of steps and adsorbed species. And the approach he advocated—using two-step reaction schemes—is as relevant today as it was when Boudart first published his book *Kinetics of Chemical Processes* in the late 1960s.

Industrial legacy

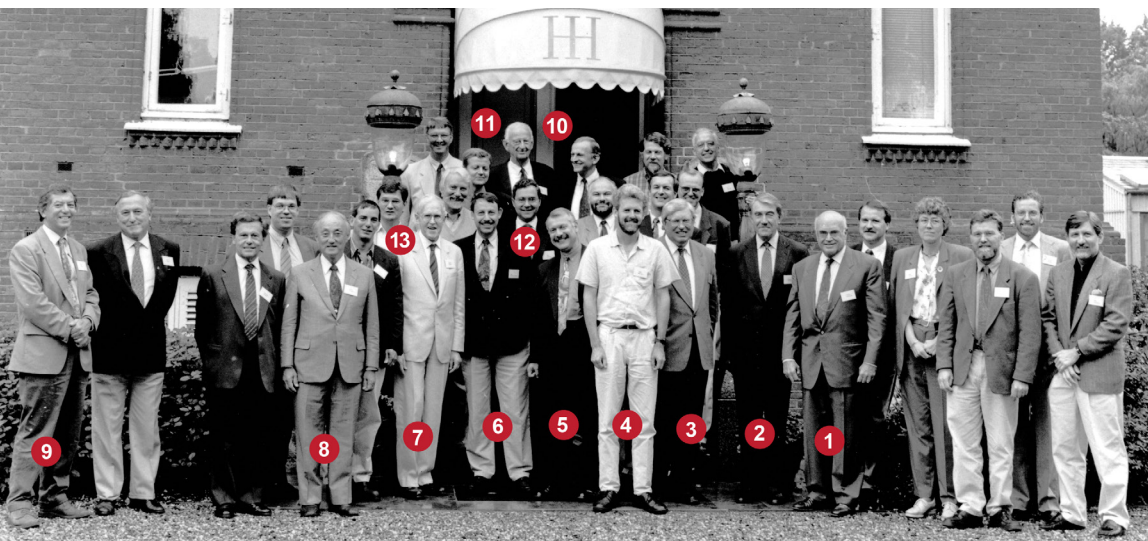
Boudart was dedicated not only to making scientific discoveries and generating insightful concepts but also to ensuring that they found their way into practice. This led to a number of important collaborations with major industrial research organizations and to his cofounding in 1974 of a consulting and contract research firm, Catalytica Associates, Inc., later renamed Catalytica, Inc. Over the decade that followed, the company became a prominent player, counting most of the world's major petroleum and chemical companies among its clients. Catalytica's proprietary research in the late 1980s and the 1990s resulted in more than 100 patents; and several subsidiaries, one of which became a leading supplier to the pharmaceutical industry, were spun off.

Boudart's impact on the practical application of catalysis started early in his Princeton career as he developed close ties with two of the preeminent industrial research laboratories of the time: Haldor Topsøe A/S in Denmark and Esso (later Exxon Research & Engineering) in the United States. Both relationships became very productive, contributing to significant advancements in industrial catalysis over the ensuing decades.

Haldor Topsøe A/S had a vital interest in finding a molecular basis for its industrial catalyst business, a concept stemming from extensive discussions between the company's

founder Haldor Topsøe and the 1922 Nobel Laureate Niels Bohr. This quest, together with the company's commercial stake in ammonia synthesis, were natural drivers for a relationship with Boudart, who had begun research in ammonia synthesis during his years at Princeton. Two senior research leaders from the company, Jens Rostrup Nielsen and A. C. Jacobsen, became visiting scholars at Boudart's Stanford lab, and Haldor Topsøe's son Henrik studied under Boudart and obtained his Ph.D. in 1972.

For his part, Boudart enjoyed participating in Topsøe's international Havreholm Meetings. For example, in 1993 he worked with Jens Norskov to arrange a symposium celebrating Topsøe's research director Anders Nielsen's 50 years in catalysis; and Boudart contributed an important paper titled "Ammonia Synthesis: The bellwether reaction in heterogeneous catalysis" (Boudart 1994b) to the meeting. The symposium attracted several top scientists in catalysis, including Gerhard Ertl (Chemistry Nobel laureate 2007), Gabor Somorjai, Sir David Anthony King, Robert Schlögl, Michael Bowker, Kenzi Tamaru, Eric Derouane, Ken Waugh, and Jim Dumesic.



Among the 1993 Havreholm meeting attendees in this photograph are: Michel Boudart (#2) flanked by two other catalysis luminaries of the last century, Gabor Somorjai (#1) and 2007 Chemistry Nobel Laureate Gerhard Ertl (#3); meeting honoree Anders Nielsen, (#7); meeting sponsors, Haldor Topsoe (#11) and Henrik Topsoe (#10); Topsoe A/G's Jens Rostrup-Nielsen (#6); co-author Jim Dumesic (#12); Sir David King (#9); Sensei Kenzi Tamaru (#8); Eric Deruane (#5); Mike Bowker (#4); Robert Schlögl (#13).

Boudart's extensive relationship with John Sinfelt at Esso began shortly after Boudart became a faculty member at Princeton. Sinfelt, who spent his career as a key contributor to the growth and eventual leadership of Esso's industrial catalysis research laboratory, joined Esso's Linden, NJ, facility in 1954. Interested in catalysis because of its importance to petroleum refining, Sinfelt frequently attended the seminars on catalysis held at Princeton, where he met Boudart. Their friendship and intellectual partnership lasted throughout their lives. Sinfelt convinced Esso to hire Boudart as a consultant, and he became one of the company's most highly valued academic contributors. A number of Boudart's students, including Robert Garten, Al Vannice, and Ricardo Levy, started their industrial research careers at Exxon after obtaining their Ph.D.s.

Sinfelt became interested in Boudart's work early on, after reading his very first publication, "Pauling's Theory of Metals in Catalysis" (Boudart 1950). In this article, Boudart analyzed observations by Shell scientist Otto Beeck that the variation in catalytic activity of ethylene hydrogenation over various metals seemed to correlate with their crystal lattice constants. Boudart immediately saw that this idea could be extended and generalized by interpreting the activity in terms of the d-character of each metal, based on Pauling's concepts of the electronic character of metals.

Eventually, thanks to Boudart's influence, Sinfelt and his team at Esso set out to control and even optimize the activity—and, more important, the selectivity—of practical catalysts by changing the d-character of metal catalysts widely used in petroleum refining. In particular, they focused on naphtha reforming, in which platinum (a Group VIII noble metal) dispersed on alumina cyclizes paraffins to form aromatics, as well as to form olefins that undergo isomerization and cracking in order to increase the octane of naphtha streams. Sinfelt chose to study combinations of alloys of different Group VIII metals, and of Group VIII and Group IB elements, as a means to tune their d-character.

Sinfelt thoroughly discussed and debated all of this work with Boudart, whom he considered one of the world's preeminent authorities on fundamental aspects of catalysis. Sinfelt also deeply appreciated Boudart's research philosophy when it came to industrial catalysis. Boudart considered progress in such a complex arena to require an astute and appropriate choice of catalytic reaction probes that closely mimic the more complex industrial process. He also advocated carrying out the reactions on catalytic solids of known and well-defined structures, determined through state-of-the-art characterization methods performed before, after and, when possible, during catalysis.

As a consequence, Sinfelt chose ethane hydrogenolysis as his probe reaction because careful study of the chemical kinetics of this reaction would provide valuable information concerning the relative rates of C-C and C-H bond scission. Boudart and Sinfelt believed that this information would be critical in designing an optimum naphtha-reforming catalyst.

Influenced by Boudart, Sinfelt also insisted on careful characterization of the catalysts that he and his group studied. At first, that meant titration of the number of metal surface atoms using hydrogen, carbon monoxide, or oxygen chemisorption. This approach became standard practice in Sinfelt's group after the publication of a classic paper by Boudart and Larry Spenadel, an Esso employee working with Sinfelt, in which the authors presented the very first hydrogen chemisorption technique to measure the dispersion of platinum on supported metal catalysts (Spenadel and Boudart 1960). Later, Sinfelt's research methods extended to magnetic susceptibility, X-ray absorption fine structure (EXAFS), infrared spectroscopy, and numerous other physical characterization tools. This work, too, was constantly discussed with and stimulated by Boudart.

All of this research led to the discovery of the following fundamental findings, which were—and continue to be—of significant industrial importance:

- a. Multimetallic catalysts are not alloys; they are multimetallic clusters. As new compositions of matter, they can be readily protected by patents.
- b. The structure and d-character of these clusters has a significant effect on catalyst activity, and especially on selectivity and catalyst life—all three being critical characteristics for catalyst design.
- c. Platinum-iridium on high-surface-area alumina is a very active and selective naphtha-reforming catalyst. This discovery led to one of the world's first processes to produce high-octane gasoline with no necessity for lead tetraethyl, the high-octane additive phased out by the U.S. Environmental Protection Agency to fulfill a legal mandate.
- d. Other bimetallic-cluster discoveries and industrial applications, such as the modification of the d-character of nickel catalysts (Group VIII) with copper (Group IB), led to an advanced hydrogenation catalyst that eliminated unwanted cracking of the hydrocarbon feedstock.

Lasting impact

Was Michel Boudart a happy man? In the eyes of his students, colleagues, family, and friends, the answer is yes. We believe that he lived a life of great fulfillment. While still quite young, Michel discovered what he was really good at: rigorous and critical scientific thinking. He charted a path that was his very own, in spite of pressure to continue the family tradition of leadership in the Belgian chemical industry. He chose a field that was very important for the world and his impact made a difference: He made the world a better place.

Michel found and lived his purpose and passion by:

- Educating and inspiring hundreds of men and women, many of whom went on to make their own positive impact on the world through the practice of catalytic science and technology in academia or industry. In his own words, this was his greatest contribution.
- Leading the development of many essential tools for catalyst characterization before, during, and after use, as well as the kinetic framework by which scientists and technologists throughout the world have been able to understand and optimize catalyst systems, many of which are vital to industrial production.
- Exerting great influence, deeply and broadly, throughout both academia and industry. Although he was a dedicated academic scientist, his contributions to the company he cofounded and to the many companies he advised were profound. His intellect and teachings left indelible imprints on people he touched.

Few scientists can claim such a deep and lasting pivotal impact on so many. This was well expressed by Channing Robertson, one of the first undergraduate students influenced by Michel at Berkeley in 1961 and later mentored by him as a Ph.D. student and faculty colleague at Stanford: “I learned so much from Michel. How to be civil. How to be respectful. How to ask tough probing questions. How to see the forest through the trees. How to seek excellence in what you do. How to see the humanity in others. My parting remembrance of Michel and of Marina: They were two people who loved to live.”

HONORS

Academy Memberships

U.S. National Academy of Sciences

U.S. National Academy of Engineering

Académie Royale des Sciences, des Lettres, et des Beaux-Arts de Belgique

Royal Belgian Academy Council for Applied Sciences

Fellow of the American Association for the Advancement of Science

American Academy of Arts and Sciences

Honorary Fellow of the California Academy of Sciences.

DOCTORATES HONORIS CAUSA

University of Liege

University of Notre Dame

University of Ghent

Institut National Polytechnique de Lorraine.

AWARDS

Belgian American Educational Foundation Fellowship, 1948

Procter Fellowship, 1949

Curtis McGraw Research Award of the American Society for Engineering Education, 1962

R. H. Wilhelm Award in Chemical Reaction Engineering of the American Institute of Chemical Engineers, 1974

American Chemical Society:

Kendall Award, 1977

Murphree Award, 1985

North American Catalysis Society:

F. G. Ciapetta Lectureship, 1986

American Institute of Chemists:

Chemical Pioneer Award, 1991

International Precious Metals Institute:

Tanaka Distinguished Achievement Award, 1994

North American Catalysis Society:

Instituted its most prestigious award for senior researchers in 2007 and named it the Michel Boudart Award for the Advancement of Catalysis. The award is presented at the Society's biennial meeting, where the recipient gives a plenary lecture.

SYMPOSIA IN MICHEL BOUDART'S HONOR:

Advances in Catalytic Chemistry III (May 1985, Salt Lake City, Utah)

The Catalysis Symposium of the 68th Colloid and Surface Science Symposium of the American Chemical Society (June 1994, Stanford University).

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